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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



## THESIS

AN ASSESSMENT OF NOGAPS PERFORMANCE IN THE  
PREDICTION OF TROPICAL ATLANTIC CIRCULATION  
FORMATION

by

Theodore G. Dorics III

June 2002

Thesis Co-Advisors:      Russell L. Elsberry  
                                 Patrick A. Harr

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**AN ASSESSMENT OF NOGAPS PERFORMANCE IN THE PREDICTION OF  
TROPICAL ATLANTIC CIRCULATION FORMATION**

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Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY**

from the

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## **ABSTRACT**

The Navy requirement for 5-day tropical cyclone track guidance necessitates an assessment of the Navy Operational Global Atmospheric Prediction System (NOGAPS) in forecasting tropical cyclone formation. The Tropical Cyclone Vorticity Tracking Program is applied to NOGAPS analyses and forecasts through 120 h to identify and track circulations in the tropical Atlantic region from 25 July - 31 October 2001. Circulations over northern South America were not found to be related to Atlantic hurricane formation and the number of formations in the western Atlantic was insufficient for statistical analysis. Circulation formations over Africa tend to be forecast too early while those forming over the eastern Atlantic tend to be forecast late. About 70% of the NOGAPS forecasts and analyzed formations are within  $\pm 12$  h regardless of forecast intervals, and about 12% of the formation forecasts are false alarms. Whereas the on-time formations tend to have small relative vorticity errors, the early (late) formation forecasts are at first too strong (weak), but then the model error growth dominates the expected timing error contribution. At the time the National Hurricane Center issues a tropical storm warning, the NOGAPS forecasts of relative vorticity, sea-level pressure, and circulation size generally have smaller amplitudes than the verifying analyzed values.



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## I. INTRODUCTION

The accuracy and timeliness of tropical cyclone track guidance are extremely important to the operations of the U.S. Navy. Afloat units underway and in-port, as well as shore stations, would greatly benefit from longer cyclone track lead times. An increase in warning times would provide increased time to evaluate, plan, and execute any actions needed to minimize damage or loss of assets and personnel.

Gradual improvements in the capabilities of global dynamical models, such as the Navy Operational Global Atmospheric Prediction System (NOGAPS), have lead to a related improvement in the accuracy of tropical cyclone track guidance. This improvement in model guidance has contributed to increased accuracy in official tropical cyclone track forecast accuracy through 72 h. This overall improvement has suggested the potential for a 5-day tropical cyclone track guidance that would address the Navy requirement. With a potential for a 5-day tropical cyclone track prediction comes the need for a tropical cyclone formation forecast, since it is quite possible for a tropical cyclone to form, intensify and move a considerable distance in 120 h.

A necessary step in assessing the potential for 5-day track forecasts is to assess current capabilities of global dynamical models to forecast tropical cyclone formation. A useful product would be a tool that would identify tropical cyclone precursors and discriminate between circulations that may not develop as strongly as predicted or cases of

predicted cyclone formation when no verifying feature occurred (i.e., false alarms). Other categories would include cyclones that develop more rapidly than predicted and cyclones that were never predicted to form (i.e., missed cyclones).

#### **A. REGIONS OF TROPICAL CYCLONE INFLUENCE IN THE NORTH ATLANTIC OCEAN**

The region of the tropical and subtropical North Atlantic Ocean is an area of heavy maritime transit, both for commercial shipping and for military operations. The potential for tropical cyclone formation exists in the Atlantic anywhere from the extreme eastern Atlantic to the western Caribbean and as far south (north) as 5° N (45° N). Four major regions in the Atlantic have environmental conditions that influence tropical cyclone formation. These regions can be defined as the eastern Atlantic formation zone, the damping zone, the western Atlantic formation zone, and the subtropical western Atlantic formation zone.

##### **1. Eastern Atlantic Formation Zone**

The region in the tropical Atlantic from Africa to about 40° W is a primary location for the formation of tropical circulations. The initial source of the circulations that form in this region lies to the east over the African continent. A midtropospheric easterly jet over western Africa is established by the extreme heating over the Sahara desert that establishes a reversed lower-tropospheric temperature gradient with higher (lower) temperatures to the north (south), which leads to easterly vertical wind shear. The strength of the jet, which is usually a maximum near 650 mb, may be strong enough to

cause the potential vorticity gradient to change sign, which is a necessary condition for instability of the mean flow (Charney and Stern 1962). At times, this sign change persists from the coast of western Africa to as far as 50° W (Dickinson and Molinari 2000) and may be responsible for growth of wave disturbances that move off the African coast.

Thermodynamic and dynamic conditions that contribute to the maintenance of the midtropospheric jet also lead to the formation of African easterly waves (AEWs). These waves tilt northeast-southwest against the horizontal shear of increasing easterly winds toward the jet maximum. With this tilt, the wave structure is favorable for a conversion of mean kinetic energy ( $\bar{K}$ ) to eddy kinetic energy ( $K'$ ) as the waves propagate westward along the equatorward side of the jet. Therefore, the large-scale circulation characteristics over western Africa are conducive to the formation and maintenance of the easterly waves. As the waves move off the west coast of Africa, they may move into an environment of relatively low sea-surface temperatures. The maintenance of the waves as they move toward the west depends on a variety of factors that include the extension of the easterly jet, surface heat and moisture fluxes, and organization of deep convection.

In addition to this primary wave formation region in the African zone, a secondary region exists north of the midtropospheric jet over Africa (Thorncroft and Hodges 2001). If the waves exhibit a northwest-to-southeast tilt, a conversion of  $\bar{K}$  to  $K'$  can occur on the poleward side of the midtropospheric jet. These waves also grow as

they move westward towards the west coast, where they may contribute to the formation of tropical cyclones.

Along the west coast of Africa, weak stationary vorticity maxima often amplify with the approach of an AEW from the east. These maxima may be localized regions between offshore trade winds poleward of the onshore winds of the summer monsoon over western North Africa. It is also possible that these localized centers are actually a product of differences in data distribution associated with the land-ocean interface along the coast.

In summary, tropical cyclone formation over the eastern North Atlantic is linked to the presence of the midtropospheric easterly jet and periphery disturbances that may amplify by drawing energy from the mean flow due to unique dynamical and thermodynamical conditions. Following formation over North Africa, the further development of the circulation is dependent on various physical mechanisms over the eastern North Atlantic Ocean. Forecast accuracy will be linked to the fidelity of the model in representing the mechanisms described above.

## **2. Damping Zone**

West of the eastern Atlantic formation zone, a region in the central Atlantic is generally unfavorable for the development of tropical circulations. Specifically, the region is unfavorable for the further development of an AEW moving into the region from the east. The damping effect on an AEW occurs for two reasons. First, the AEW moves into a relatively cool oceanic current regime. Second, the AEW is moving away from the  $\bar{K}$  to  $K'$  energy source that initiated and sustained the AEW.



The AEW formed over Africa where the low-level regime is a warm, relatively moist area with release of convective instability in advance of the rapidly moving AEW. Over the ocean, the lower troposphere will be cool and less unstable, especially in the trade wind regime with the capping trade wind inversion. In the trade wind regime, the easterlies reverse to westerlies aloft and such a vertical wind shear is unfavorable for tropical cyclone formation.

As an AEW moves west, it typically experiences a loss or diminishing of the energy sources that initiated and sustained the AEW during its passage across Africa. Whereas the midtropospheric jet over Africa is initiated by a reversed temperature gradient (and easterly vertical wind shear) because of the extreme heating over the Sahara Desert, this reversed temperature gradient is not present over the Atlantic Ocean. Although the midtropospheric jet may continue some distance beyond the coast, the  $\bar{K}$  to  $K'$  conversion mechanism will be diminished. Likewise, the weak baroclinic energy conversion in the waves over Africa will be lost. While frictional dissipation will be decreased over the ocean relative to over land, this is of little benefit because the maximum winds for the AEW are at the midtroposphere and the surface winds are relatively weak.

### **3. Western Atlantic Formation Zone**

The eastern Atlantic formation zone extends to about 40° W. Waves that propagate into the central Atlantic often undergo damping due to several reasons related to a departure from environmental conditions that initiated the wave formation. Waves that have not developed into

tropical cyclones prior to entering the central Atlantic are unlikely to do so until they make the transition through the damping zone and reach the western Atlantic.

If a wave makes the transit across the eastern Atlantic while remaining intact, it may form into a tropical cyclone after it arrives in the western Atlantic formation zone, which is a more favorable environment for tropical cyclone formation than the region along the African coast. Although the seedling forming into a cyclone may often be traced back to origins over the African continent, it is the higher sea-surface temperatures, the increase in near-surface moisture, and the higher trade wind inversion of the western Atlantic that contribute to tropical cyclone genesis. For the purposes of specifying formation zones, the onus is not necessarily on determining the source region of the disturbance that eventually becomes a tropical cyclone, but rather to broadly identify regions where formation is most common.

#### **4. Subtropical Western Atlantic Formation Zone**

The fourth major formation zone is in the subtropical western Atlantic, where two distinct formation mechanisms may be responsible for a significant number of tropical cyclone formations. First, baroclinic front formation occurs when a stagnating front, usually originating from North America, penetrates offshore and over the warmer coastal oceans. This stagnant baroclinic zone is characterized by asymmetric vorticity isolines. It may take several days before a dominant vorticity maximum forms, and eventually leads to a tropical cyclone. The

other formation type in the subtropical western Atlantic formation zone occurs when a strong upper-level low penetrates downward and becomes the initial perturbation for a tropical cyclone. The upper-level divergence associated with the upper-level low may also indirectly contribute to intensifying a pre-existing wave in the easterlies.

## **B. PLAN FOR THESIS**

In this thesis, the capability of NOGAPS to forecast the formation of circulations that may later become tropical storms and hurricanes over the tropical Atlantic is investigated. Circulations, defined by relative vorticity at 850 mb, will be identified in analysis and forecast fields. The primary emphasis is during the formation period of each circulation. Analyzed and forecast circulations will be tracked from initial detection until they develop into a tropical cyclone or dissipate. Comparisons between analyzed and forecast circulations will be made to evaluate the NOGAPS capability to forecast formation based on several physical characteristics that are known to be important in formation.

For the purpose of this study, the tropical North Atlantic will be divided into four geographical regions that may have different influences affecting circulation formation and their potential development into a tropical cyclone. Knowledge of the performance of NOGAPS in forecasting formation, developing, and non-developing circulations can assist the forecaster in interpreting the NOGAPS products when such a circulation is forecast to

develop in one of the four primary regions of the tropical North Atlantic.

## II. METHODOLOGY

A large number of analyzed and forecast fields must be examined to assess the potential for tropical cyclone formation. The technique summarized here uses the Tropical Cyclone Vorticity Tracking Program (TCVTP) developed by Professor Patrick Harr. This program, which is summarized in Figure 2.1, synthesizes model representations of vorticity centers to define circulations that may or may not intensify into a tropical cyclone. It provides a method for an objective detection of centers and then summarizes a number of formation-related environmental parameters associated with each center throughout its life cycle.

### A. MODEL DATA

The model fields used in the analysis (Table 2.1) are Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses and forecasts at 06, 12, 18, 24, 30, 36, 42, 48, 60, 72, 84, 96, and 120 hours. Since the area of interest is Atlantic tropical cyclones, the spatial domain covers 140W - 0W and from the equator to 40N. Model resolution is one-degree latitude and longitude, and the time resolution is 12 h (00 UTC and 12 UTC). Forecasts initiated at 06 UTC and 18 UTC were only begun in March 2002, and thus were not available for the 2001 hurricane season, but will be available for the 2002 hurricane season. The period of study is from 25 July - 31 October 2001, which covers tropical storm Barry through tropical storm Lorenzo.

Table 2.1. NOGAPS fields used in the TCVTP analysis.

relative vorticity ( $10^{-5} \text{ s}^{-1}$ )
sea-level pressure (mb)
latent heat flux (surface) ( $\text{W m}^{-2}$ )
shallow vertical wind shear (500 - 850 mb)( $\text{m s}^{-1}$ )
deep layer vertical wind shear (200 - 850 mb)( $\text{m s}^{-1}$ )
geopotential height thickness (1000 - 200 mb) (gpm)
1000 - 500 mb temperature difference (K)
vertical motion ( $\text{Pa s}^{-1}$ )
total precipitation ( $\text{kg m}^{-2}$ )
vapor pressure (Pa)

## B. ANALYSIS PROCEDURES

Figure 2.1 is a summary of the steps used in the TCVTP. The sections following this figure describe each step of the process. Each box along the center of Figure 2.1 is numbered to correspond to the following subsections that describe the processing contained in the TCVTP procedure.

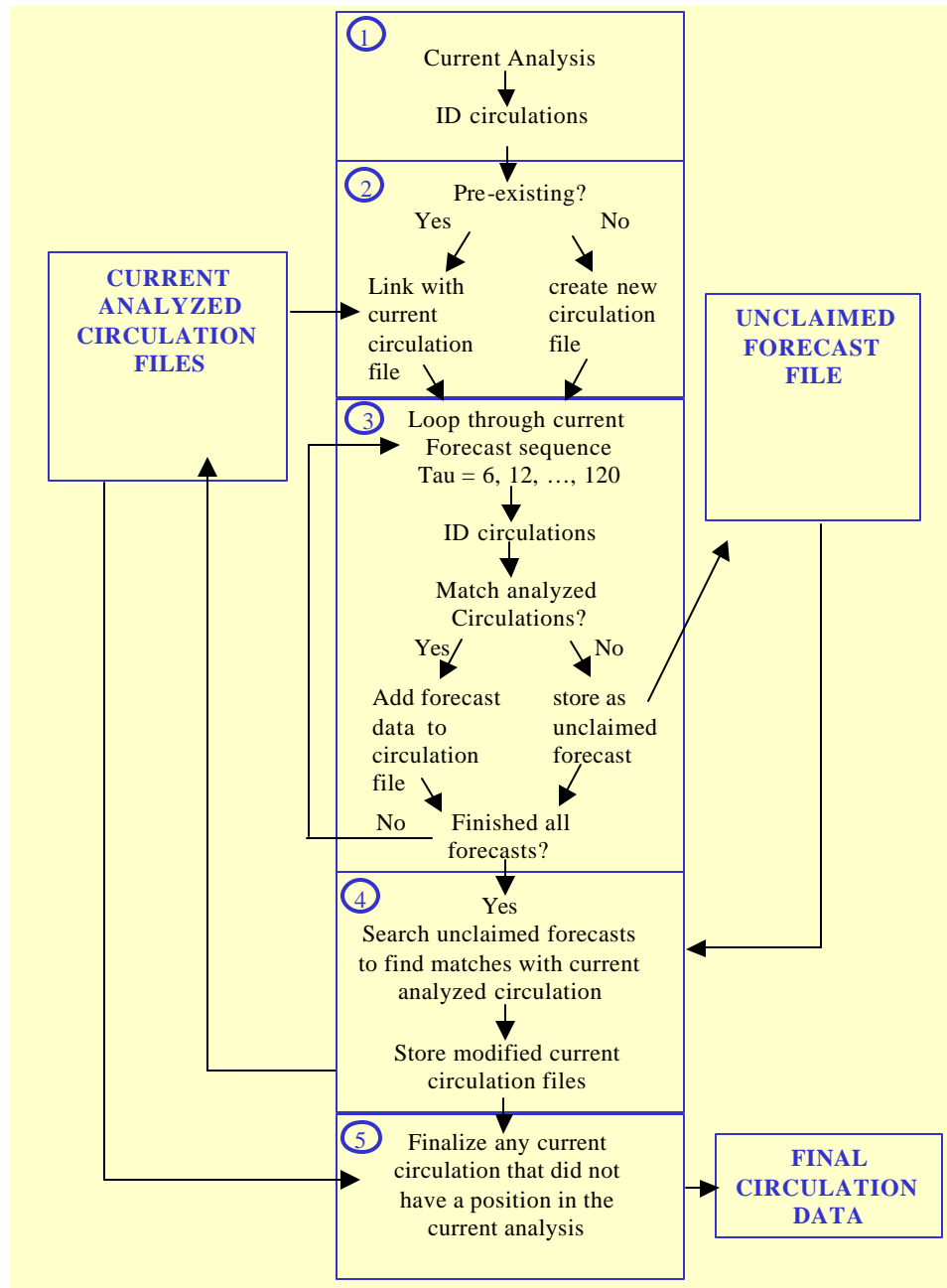


Figure 2.1. A description of the steps followed in the TCVTP process.

## 1. Analyzed Circulation Identification

As part of the first step in Figure 2.1, relative vorticity at 850 mb from NOGAPS is computed to form the basis for identification of circulations. All relative vorticity maxima greater than  $1.0 \times 10^{-5} \text{ s}^{-1}$  are identified as trackable circulations. The 850 mb relative vorticity analysis field for the current model integration is examined first. For each trackable circulation, an ellipse is fit to the outer closed vorticity contour that is at least  $1.0 \times 10^{-5} \text{ s}^{-1}$ . Figure 2.2 is an example of an ellipse fit to the outer closed vorticity contour in a NOGAPS 850 mb relative vorticity field. The ellipse-fitting routine is based on the multivariate (east-west, north-south) normal probability distribution and is defined to span the 0.95 probability level of the distribution. The center of the ellipse is defined as the position of the relative maximum in the relative vorticity field, and the size of the circulation is defined to be the area of the ellipse.

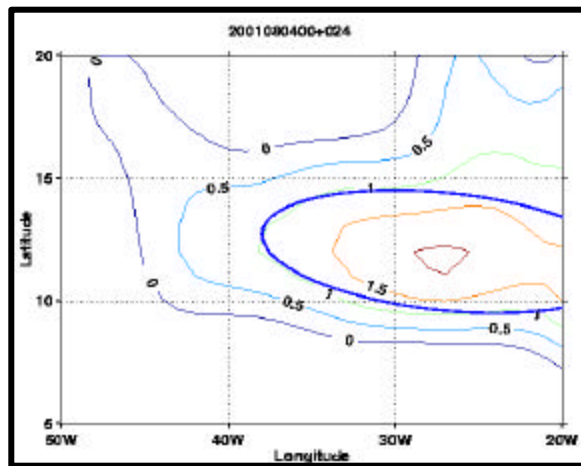


Figure 2.2. An example of an ellipse fit to a vorticity contour of  $1.0 \times 10^{-5} \text{ s}^{-1}$  that defines a circulation in the 24-h NOGAPS forecast initiated at 00 UTC 04 August 2001.



## **2. Identifying Tracks of Analyzed Circulations**

In step 2 of Figure 2.1, the identified circulations from the current model analysis are compared to circulations that were identified in the analysis 12 hours prior. This comparison is made to see if the recently identified circulation can be "matched" to a previously identified circulation stored in the analyzed circulation directory of the TCVTP (left box in Figure 2.1). This directory contains all previously analyzed circulations that are currently active. The distance and the direction of the new circulation relative to each previous circulation is used to match circulations in the current analysis with previously analyzed circulations. The distance and direction criteria vary based on the translation speed of the analyzed circulation. If the prior translation speed is small, the allowable direction orientation to the new circulation is relaxed to allow for a stalled situation. When a circulation from the current analysis is matched to a pre-existing circulation, it becomes the next point of that circulation track. If the circulation cannot be matched, then the unmatched circulation is stored as a new file in the analyzed circulation directory, where it will be compared to circulations in subsequent analyses.

Information used to identify each circulation and characterize the ellipse fitted to each analyzed circulation is given in Table 2.2. Analyzed circulations are assigned a unique identifier (atlyyyymmddhh\_lat\_lon), where yyyy is the year, mm is the month, dd is the day, hh is the time, lat is the initial latitude, and lon is the

initial longitude corresponding to the time and location of first appearance in the NOGAPS analysis. Tracks are thus identified by the designation given to the first analyzed circulation position in the series. Each circulation is also described by the vorticity shape, size, and orientation of the ellipse fit to the outer closed vorticity contour (2.2a).

Table 2.2. (a) Parameters used in the ellipse-fitting to identify analyzed and forecast circulations. (b) Additional parameters used to characterize each circulation for matching with circulations in the previous 12-h (6-h) analysis (forecast) where available.

size (number of grid points) shape -ellipse major axis -ellipse minor axis -angle of the major axis w/r to north -correlation of axes	name: atlyyyymmddhh_lat_long current date-time-group yyyymmddhh forecast time (for forecast circulations) latitude longitude
a.	b.

In addition to the identifier and ellipse characteristics, the NOGAPS fields listed in Table 2.1 are used to calculate average values of other atmospheric variables over each ellipse to characterize each circulation (Table 2.3). These variables that are commonly associated with tropical cyclone formation may be used to distinguish characteristics of forecasts that are accurate or inaccurate. As a circulation is tracked, a history file of the variables in Table 2.3 is created that contains one line per analysis (or forecast) field associated with the circulation. These history files will be the basis for analysis of the model forecast accuracy.

Table 2.3. Average or maximum/minimum values of the atmospheric variables listed in Table 2.1 that are calculated for each circulation.

average sea-level pressure (SLP)	maximum temperature difference
minimum SLP	quadrant averages of temperature difference
quadrant averages of SLP	average vertical motion
average latent heat flux	maximum vertical motion
maximum latent heat flux	quadrant averages of vertical motion
quadrant averages of latent heat flux	average precipitation
average shallow vertical shear	maximum precipitation
average deep layer vertical shear	quadrant averages of precipitation
average height thickness	average vapor pressure
maximum height thickness	maximum vapor pressure
quadrant averages of height thickness	quadrant averages of vapor pressure
average temperature difference	<i>*(minimum and maximum values and locations are included if they exist, otherwise 999)</i>

### 3. Forecast Circulation Identification

In step 3 of Figure 2.1, The same ellipse-fitting process described in section II.A.1 is applied to all 850 mb relative vorticity forecast fields from the current model integration. An ellipse is fit to all relative vorticity maxima that meet the threshold criteria to define circulations from all forecast times in the current model integration. All variables listed in Tables 2.2 and 2.3 are assigned to forecast circulations as well.

After the circulations in the forecast fields are identified they are compared to circulations that were identified in the current analysis. A comparison is also made to link forecast circulations in all forecast fields (+6 h, +12 h, etc.) of the current model integration. Those forecast circulations that are matched with analyzed circulations become the evolution forecasts for the analyzed circulations. Despite the addition of a forecast circulation to the track, the track is still identified by the identifier of the first analyzed circulation in the track. Forecast circulations that are not matched to analyzed circulations are stored in the unclaimed forecast circulation directory of the TCVTP with other unmatched forecasts from previous model integrations. Unmatched forecast circulations are named based on the forecast time in which they first appear.

#### **4. Linking Forecast Circulations from Previous Model Integrations with Analyzed Circulations from the Current Model Integration**

The forecast circulation directory (right box of Figure 2.1) contains all forecasts not yet matched to an analyzed circulation. In step 4 of Figure 2.1, all unmatched forecast circulations from previous model integrations are now compared to the analyzed circulations from the current model integration. If the matching criteria are met, unclaimed forecast circulations from the forecast circulation directory are attached to the analyzed circulation and become the formation forecasts for the analyzed circulation.

## **5. Finalization of Tracks and Forecasts**

As shown in step 5 of Figure 2.1, there are only two outcomes from this process. The first outcome is the finalization of a tracked circulation. When no subsequent model integration produces a circulation that can be matched with an existing track, the track is finalized and stored in the final circulation directory. This collection of completed tracks represents the data available for further analysis. The second outcome is a failure to successfully match a forecast circulation with an analyzed circulation. This results in storage of the forecast circulation such that it can be assessed as a potential false alarm.

### **C. QUALITY CONTROL AND POST-PROCESSING**

As with any automated process, quality control measures are needed when analyzing model fields with the TCVTP. The program only identifies a circulation when it meets the specified threshold criteria. In addition, individual circulations are joined together to form tracks only when the translation speed and track orientation threshold criteria are met. On a few occasions during the study period, the NOGAPS model fields were not available, which resulted in data gaps for tracks. While this was not a fault of the TCVTP, such instances necessitate a thorough examination of the next TCVTP output to ensure representative tracks from the NOGAPS analysis and forecast fields. Application of the TCVTP in this study did not indicate systematic errors in the program for which code could be written to automatically correct for gaps or misidentifications in the TCVTP process. Until such

automated quality control steps can be developed, a human must be in the loop. However, this would normally require only a few minutes each analysis time because most of the tracks are continuous and missing analyses would be rare in real-time operation (vice dealing with archived analyses as in this study).

### III. ANALYSIS AND RESULTS

#### A. TRACKED VORTICITY CIRCULATIONS

The TCVTP was used to track all circulations meeting the threshold 850-mb relative vorticity criteria in the tropical Atlantic from 25 July - 30 October 2001. The resulting collection of 121 circulations was categorized according to the geographic region at the initial detection. The circulations were further categorized by the length of time (less or greater than 48 h) they were tracked in the analyses. In some cases, an additional classification was whether the first analysis appearance occurred over Africa or over the eastern Atlantic Ocean.

Figure 3.1 is a depiction of all circulations and their respective tracks from TCVTP, while Table 3.1 lists the track classifications mentioned above, excluding the South American circulations for reasons explained in section III.A.1 below.

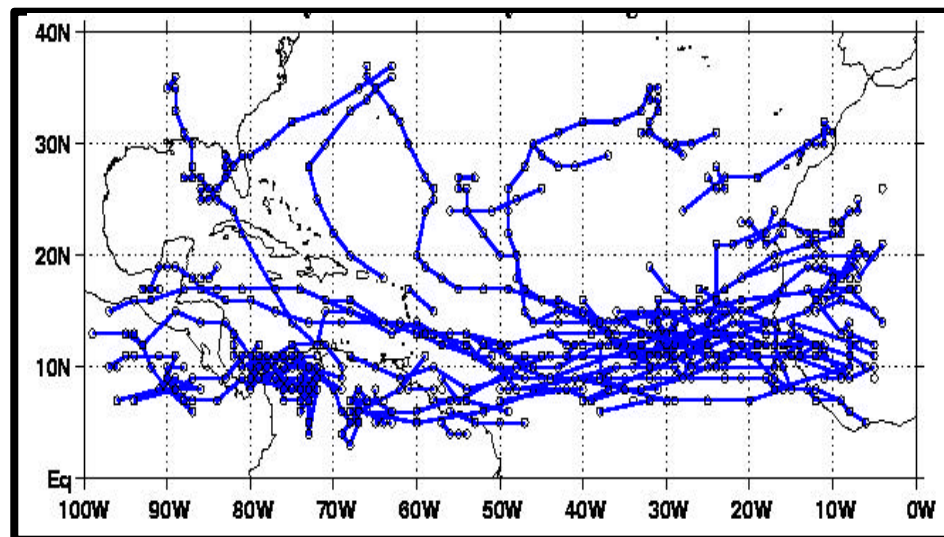


Figure 3.1 All tropical Atlantic circulations tracked in the NOGAPS analyses during 25 July - 30 October 2001.

Table 3.1. Number of tracks in various categories during 25 July - 30 October 2001 after exclusion of the South American tracks in Figure 3.1.

Tropical Atlantic	121
Western Atlantic	19
At Least 2 Days	6
Less Than 2 Days	13
Eastern Atlantic	67
At Least 2 Days	38
1 <sup>st</sup> Analysis Over Ocean	21
1 <sup>st</sup> Analysis Over Land	17
Less Than 2 Days	29
Reached Ocean	16
Never Reached	13

### **1. South American Continental Formation**

Of the 121 tracks identified by TCVTP (Figure 3.1), 35 circulations formed over the northern portion of South America. This region is characterized by a broad, permanent region of cyclonic vorticity. Whereas some of these circulations remained quasi-stationary over the continent, others propagated towards the west, and frequently continued over the Pacific Ocean. Because of the nature of the formation region and because of the typical direction of propagation away from the Atlantic hurricane formation regions, these 35 tracks were eliminated from further analysis procedures.

### **2. Western Atlantic Formation**

Nineteen circulations formed west of 40° W (Figure 3.1), and were classified as western Atlantic formations.



The longitude 40° W was selected as the eastern limit of this formation region to facilitate the assessment of model performance in forecasting circulations entering the damping zone. Circulations forming west of 40° W and moving to the west would be either forming in the damping zone or moving into the damping zone shortly after formation. Circulations forming farther east near Africa would have had sufficient time to develop prior to entering the central Atlantic.

These 19 circulations identified in the western Atlantic were further grouped by the length of time they appeared in analyses. Tracks were categorized as being less than two days or at least two days. Categorizing the tracks in this manner was a way to separate the tracks that eventually developed into long-lived vorticity circulations and potentially tropical cyclones. Six circulations had tracks of at least 2 days and 13 had tracks of less than 2 days.

### **3. Eastern Atlantic Formation**

The region accounting for the majority of the TCVTP-tracked circulations was the eastern Atlantic. Sixty-seven tracked circulations formed in the eastern Atlantic between 0°W to 40°W (Figure 3.1). The majority of these tracked formations had histories that could be traced to a developing easterly wave over western Africa. As in the western Atlantic described above, the eastern Atlantic vorticity circulations were grouped by length of time in the analyses. The eastern Atlantic category had 38 tracks of at least 2 days and 29 tracks of less than 2 days.

Eastern Atlantic tracks of at least 2 days were subdivided into circulations that had a first analysis appearance over the Atlantic Ocean (21) and circulations that had a first analysis appearance over Africa (17). Eastern Atlantic tracks lasting less than two days were subdivided into circulations that either formed or moved over the ocean (16) and circulations that formed over land and never made it to the ocean (13). Perhaps the most surprising result of this limited sampling of circulation formations is the numbers over the eastern Atlantic versus over Africa. The prior studies of regular AEW passages might have suggested that the great majority of circulations would have been over Africa, and that the eastern Atlantic would have been a dissipation zone rather than a primary formation zone. This is probably due to the use of the 850 mb level rather than 700 mb or 600 mb, which is the level of maximum AEW circulation during the formation period.

## **B. FORECAST ERRORS**

Tracked circulations from the eastern and western Atlantic regions were examined to diagnose possible recurring errors that might be common to a specific track category. Analysis of the NOGAPS forecasts was performed for each track, both at the formation time and at the end of the track.

### **1. Formation Forecast Assessment**

All circulation forecasts were analyzed to assess how well the model prediction for formation agreed with observed formation events. Forecasts were either on-time, early, or late. The strictest criteria were set for

determining an on-time forecast. Specifically, the formation forecast time had to exactly coincide with the first appearance of a relative vorticity maximum in an analysis. A more relaxed condition was also tested wherein a +/- 12-hour error was allowed, with corresponding modifications in the definitions of late and early formation errors.

**a. *Western Atlantic***

For the 19 circulation formations in the western Atlantic, 50 forecasts were made prior to the actual appearance of a vorticity circulation in an analysis. When applying the strict (relaxed) definition of on-time to these forecasts, 23 (39) were on-time, 18 (5) were early, and 9 (6) were late. Due to a limited number (20) of formation forecasts for circulations tracked at least 2 days, analysis did not produce a trend of more early forecasts or more late forecasts. The number of on-time, early, and late forecasts were 11, 5, and 4, respectively. However, the circulations lasting less than two days had more than twice as many early formation forecast errors than late errors (13 versus 6). Unfortunately, the number of circulations tracked in the western Atlantic did not provide enough cases for an in-depth analysis of a forecast timing error trend. Therefore, a tabular error summary for western Atlantic formation forecasts is not included. A data set consisting of more western Atlantic circulations would be required before assessing any formation forecast error trends in NOGAPS.

### ***b. Eastern Atlantic***

Table 3.2 summarizes the error in forecasts made for the 67 tracked circulations in the eastern Atlantic. Errors based on both strict and relaxed definitions are included. Forecasts in this region are categorized by whether the forecasts were made for circulations forming over Africa or the eastern Atlantic Ocean, as well as by whether the circulation lived less than or more than 2 days. Additionally, forecasts are subdivided by the formation forecast error categories (on-time, early, or late).

Table 3.2. Summary of formation forecast timing errors (On-time, early, and late) based on both strict and relaxed on-time criteria for categories of circulations forming in the eastern Atlantic zone.

	STRICT ON-TIME CRITERIA			RELAXED ON-TIME CRITERIA		
	On-time	Early	Late	On-time	Early	Late
<b>At least 2 days</b>						
Formation over Africa	35	35	18	59	16	9
Formation over E. Atlantic	19	6	29	39	1	14
<b>Less than 2 days</b>						
Never reached ocean	29	16	5	45	4	1
Reached ocean	8	7	23	4	4	7

This zone yielded several interesting error trends for the formation forecast assessment of NOGAPS. A total of 226 forecasts were made for the circulations forming in the eastern Atlantic. Without considering the forecast interval, 91 (170) of these were on-time, while 135 (56) were either early or late following the strict (relaxed) criterion for an on-time forecast. Although this significant reduction of formation timing errors for the relaxed criterion is interesting, the remainder of this

section pertains to the errors resulting from application of the strict criteria, except where noted.

Focusing on the eastern Atlantic circulations that had tracks of at least two days, 35%, 11%, and 54 % of forecasts for circulations first appearing over the eastern Atlantic Ocean were on-time, early, and late, respectively. On the other hand, for circulations forming over Africa, 42%, 36%, and 21% of forecasts were on-time, early, and late, respectively. This trend continues when examining the eastern Atlantic circulations tracked less than 2 days. For circulations that formed over the ocean, or were tracked over the ocean at some point in their history, 19%, 19%, and 62% of the forecasts were on-time, early and late, respectively. For circulations that never tracked over the ocean, 58%, 32%, and 10% of the forecasts were on-time, early, and late, respectively. It is concluded based on this sample that circulations forming over Africa are forecast by NOGAPS to form too early while circulations forming over the eastern Atlantic are forecast to form later than they actually do.

A concern to the operational forecaster is the accuracy of formation forecast timing relative to the length of time prior to actual formation. That is, high rates of timing errors for forecasts made 12 h prior to formation would be a greater concern than high rates occurring in forecasts made 120 h prior to formation. Table 3.3 summarizes the occurrence on-time, early, and late formation forecasts based on time (< 2 days, 2-3 days, or > 3 days) prior to formation.

Table 3.3. Summary of formation forecast timing errors for both strict and relaxed on-time criteria. Forecasts are those made for all circulations forming in the eastern Atlantic Ocean, and are categorized based on the time the forecast was made relative to actual formation (< 2 days, 2-3 days, or > 3 days).

Time prior to actual formation	STRICT ON-TIME CRITERIA			RELAXED ON-TIME CRITERIA		
	Early	On-time	Late	Early	On-time	Late
> 3 days	15	12	1	8	20	0
2-3 days	31	22	25	13	49	11
< 2 days	18	57	49	4	78	20

With forecasts made greater than 3 days prior to formation, it is more likely (unlikely) to have early (late) forecasts as integrations only take place out to 120 h. This is borne out for both strict (only 1) and relaxed (0) late forecasts. The one late forecast and seven of the early forecasts were within 12 h, so with the relaxed criterion the on-time performance (71%) is quite good compared to the early forecasts.

With forecasts made less than 2 days prior to formation, the predominant tendency would be for more late forecasts than early forecasts. This is borne out for the strict and relaxed cases as well. In the latter case, an appearance in the initial fields of the -12 h forecast would satisfy the relaxed criterion. The 76% relaxed on-time performance in these short-term forecasts is considered favorable.

For the intermediate intervals, both early and late forecasts might be expected, but with the strict definition a slight tendency for early forecasts exists. With the relaxed definition, the early and late forecasts are essentially the same, and 49 of 73 (67%) of the forecasts are on-time. In all three categories, relaxed on-time is close to 70% (as earlier summarized), which indicates almost no dependence on the times the forecasts were made relative to actual formation.

## **2. End-of-Track Forecast Assessment**

While the primary emphasis in assessing NOGAPS performance is placed on the forecast of formation events, forecasts made for the end of a circulation track are also of interest. That is, if a circulation actually dissipates before leading to a tropical cyclone formation, it is important for NOGAPS to also forecast that scenario. Examining end-of-track forecasts may reveal instances where NOGAPS tends to forecast a vorticity circulation to exist longer or dissipate earlier than it actually does. These possible instances would be over-forecasts or under-forecasts of a circulation's lifespan. When the error occurs shortly after formation, it can be viewed as a type of formation forecasting error. Figure 3.2 is a summary of end-of track forecasts for the western and eastern Atlantic circulations that appeared in analyses less than 2 days. Notice that although a few of the forecasts terminate the circulation prematurely (dots to left of vertical axis), the predominant tendency is clearly for too long life-spans for this sample.

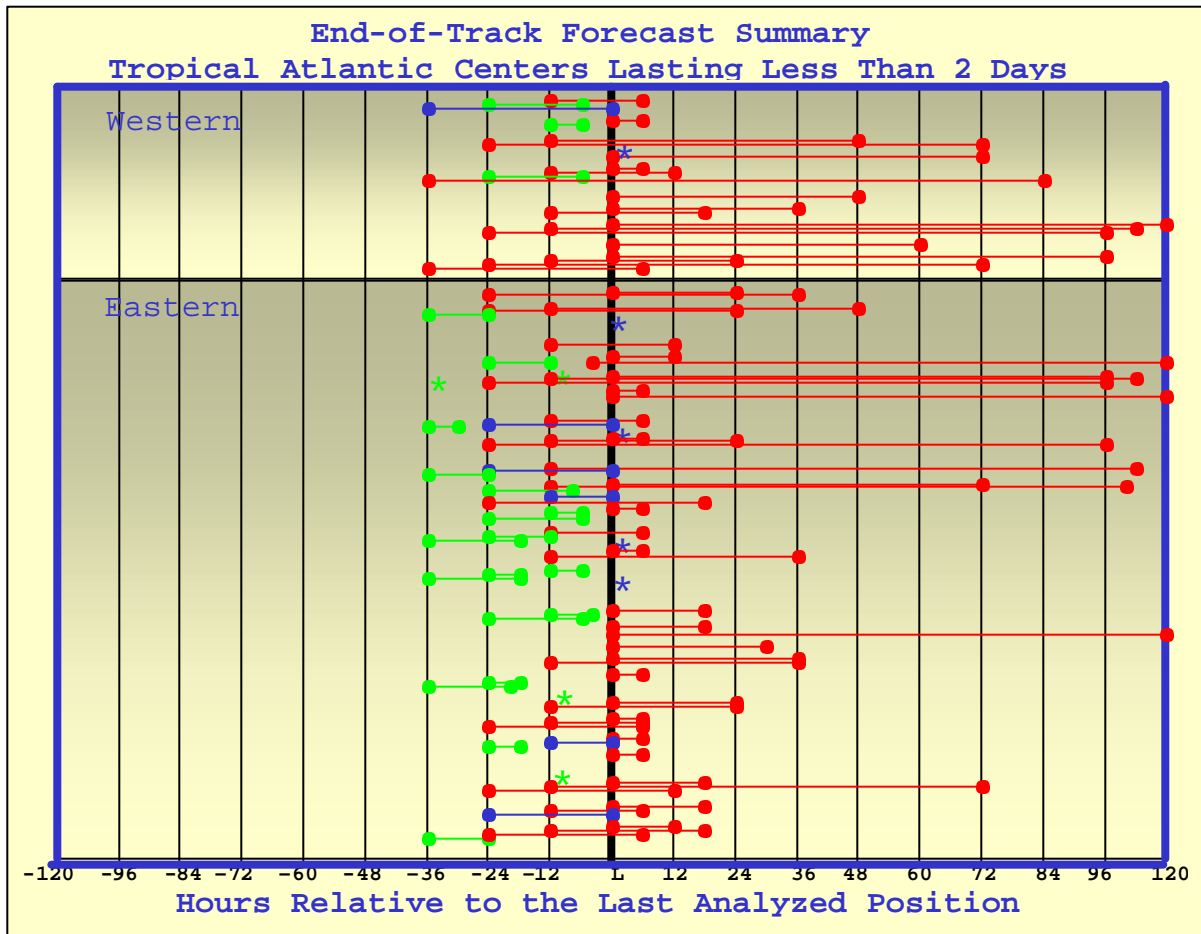


Figure 3.2. Summary of all NOGAPS forecasts of formation (left dot) and the end of a circulation (right dot) for circulations in the western (top section) and eastern (bottom section) Atlantic Ocean that lived less than 2 days. The x-axis represents time relative to the last appearance of a circulation in an analysis. Forecasts that under-predicted, accurately predicted, and over-predicted circulation lifespan are represented by the green, blue, and red lines, respectively.

#### ***a. Western Atlantic***

In the western Atlantic, only 13 circulations were tracked for less than 2 days. For these circulations, a total of 24 forecasts were made between the time of the first appearance in an analysis and the last analysis appearance. Only 3 of the 24 exactly predicted the final



time a circulation would appear in an analysis. The vast majority of the forecasts (19) predicted that the circulation would live longer than it actually did, as is evident by the abundance of red (long) lines in Figure 3.2. This may indicate a tendency for NOGAPS to over-forecast the life expectancy of relatively weak western Atlantic vorticity circulations, which is an error similar to a false alarm.

#### ***b. Eastern Atlantic***

For the 29 vorticity circulations tracked less than 2 days in the eastern Atlantic formation region, 80 forecasts were made between the first analysis appearance and the final analysis appearance of the circulations. Overall, only 11 forecasts met the strictest criteria for predicting the end of a circulation's appearance in the analysis by exactly coinciding with the final appearance. Conversely, 47 forecasts were predictions that the circulations would persist longer than they actually did (Figure 3.2). As in the western Atlantic cases, this would indicate a model tendency to over-forecast a circulation's lifespan, and thus create a false alarm-type error.

### **3. Special Error Categories**

#### ***a. Missed Formations***

Other types of errors were present in the forecasts for the circulations forming in the tropical Atlantic. One type of error that occurred in both regions was a missed formation. In these instances, a circulation appeared in an analysis without any prior forecasts for formation. Three circulations in the western Atlantic were tracked in the NOGAPS analyses that never were detected in

a forecast. In the eastern Atlantic, nine circulations formed without detection in a NOGAPS forecast. Specifically, all nine of the missed formations were circulations that formed over the eastern Atlantic Ocean rather than over Africa, which would indicate that ocean formations are more difficult to predict than formations that occur over land. In addition, five of the nine missed circulation formations were for circulations that lived at least 2 days. Thus, the error is not restricted to short-lived vorticity circulations with short tracks.

***b. Skipped Forecast Periods***

Figure 3.3 is a depiction of a forecast sequence that includes a skipped forecast period, which can be likened to an under-forecast error. In this case, a circulation that appeared in an analysis at time 00 h was forecast to appear in all model integrations initiated between -96 h and -48 h, and again between -24 h and -12 h. Even though only the last two forecasts had the correct timing, each of these forecasts included a formation. However, the -36 h model integration did not include a forecast for the same vorticity circulation. Thus, this forecast is defined to be a skipped forecast.

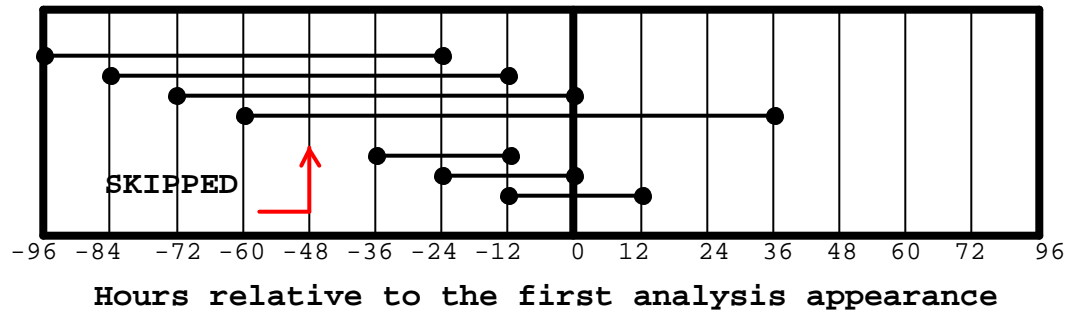


Figure 3.3. Example of a series of forecasts initiated at the time of the left dot that forecast a circulation formation at the time of the right dot. However, the forecast that was initiated at -36 h did not predict a formation, which is then defined as a skipped forecast.

This skipped forecast error was a common occurrence in both the western and eastern Atlantic regions. The highest ratio of skipped forecasts-to-forecasts made was for the eastern Atlantic circulations that formed over the ocean or were tracked over the ocean at some point. For the 91 formation forecasts in these cases, there were 21 skipped forecasts. The skipped forecasts could simply be a result of the forecast 850 mb vorticity value temporarily being below the threshold value. Still, the phenomena should be viewed as an error since an analyzed circulation did form. The larger occurrence of skipped forecasts over the ocean than over Africa may be attributed again to the data distribution differences with fewer and more erratic observations over the ocean.

### ***c. False Alarms***

Forecasts for a circulation formation without the appearance of a circulation in an analysis are classified as false alarms. The criteria here for a false alarm event are that the forecast circulation had to be tracked for at

least two consecutive forecast intervals, and that the circulation had to appear in at least two consecutive model integrations, or no more than 24 hours between forecast appearances.

Figure 3.4 is a depiction of the 14 false alarms in the tropical Atlantic meeting these criteria during 25 July - 30 October 2001. Notice that some of these false alarms persisted for the minimum of 24 h, but others persisted for as long as 60 h. Only one long-lasting, quasi-stationary false alarm was initiated over Africa. All of the remaining cases were over the Atlantic. Six false alarms were initiated east of  $40^{\circ}$  W, while the other eight began west of  $40^{\circ}$  W. This leads to a much higher false alarm rate in the western Atlantic (32%) than in the eastern Atlantic (9%). The total false alarms (14) vice the total number of formations (86) gives a rate of about 12%.

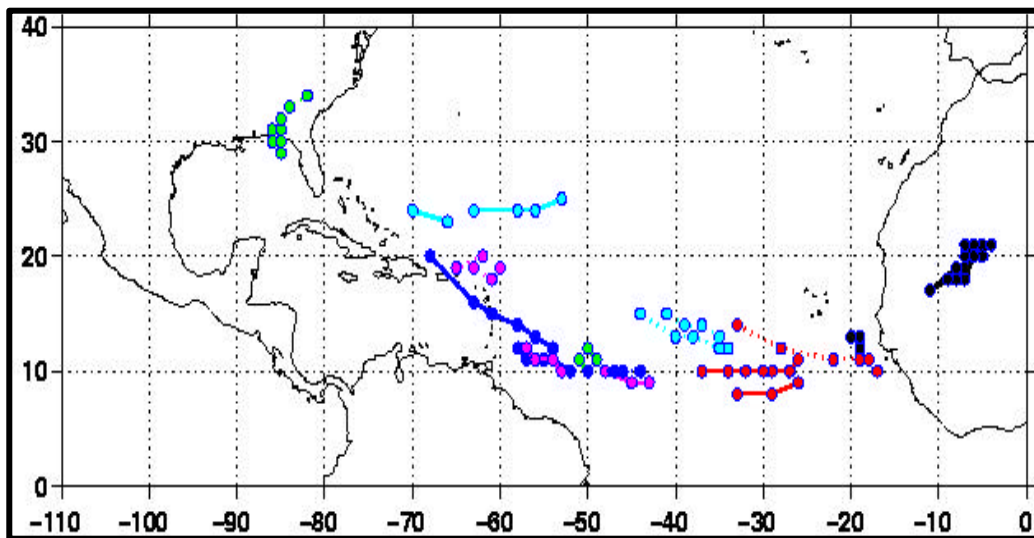


Figure 3.4. Plot of all false alarm errors for the period of the study. Track points and tracks of the same color that are grouped near one another indicate forecasts related to the same circulation.

### **C. VERIFICATION OF FORECAST VARIABLES**

Verifying the value of a given forecast variables against the actual value from an analysis is one way to assess the performance of NOGAPS forecast of vorticity circulation formation. One goal of the verification is to explain the over development or under development of vorticity circulations in relation to formation timing errors.

In this study, verification is performed using two methods. The first method consists of comparing the forecast values of a given variable from a group of forecasts with the actual value observed at the analysis time. Forecast values of relative vorticity and sea-level pressure (SLP) from various forecast times are verified against observed values at the corresponding analysis time.

The second method involves verifying a group of forecast values against observed values once a specific vorticity or storm strength threshold is reached. In this study, the forecast variables are compared to the analysis values at times when circulations reached a vorticity of  $2.5 \times 10^{-5} \text{ s}^{-1}$  and  $3.0 \times 10^{-5} \text{ s}^{-1}$ , as well as at the time of the first warning issued by the National Hurricane Center.

#### **1. Verification of Forecast Variables Against Values at First Appearance**

The procedure for verifying a forecast value against the actual value in the verifying analysis will be explained with the schematics in Figures 3.5-3.7. The x-axis in each figure represents hours relative to the first

appearance of a circulation with 850-mb relative vorticity greater than  $1.0 \times 10^{-5} \text{ s}^{-1}$ .

As an example of this verification method, assume that at time -36 h (Figure 3.5) a 36-h NOGAPS forecast was for the formation of a vorticity circulation (boxes a, b in Figure 3.5). Subsequent forecast values at 48 h, 60 h, ..., 120 h predict the evolution of this circulation that formed on-time (box c). The forecast for circulation formation is on-time in that a circulation did form at time 00 h (box d). Since the 36-h forecast involves no timing error, the forecast value of vorticity or SLP from the 36-h forecast would be verified against the value observed in the time 00 h analysis (box e).

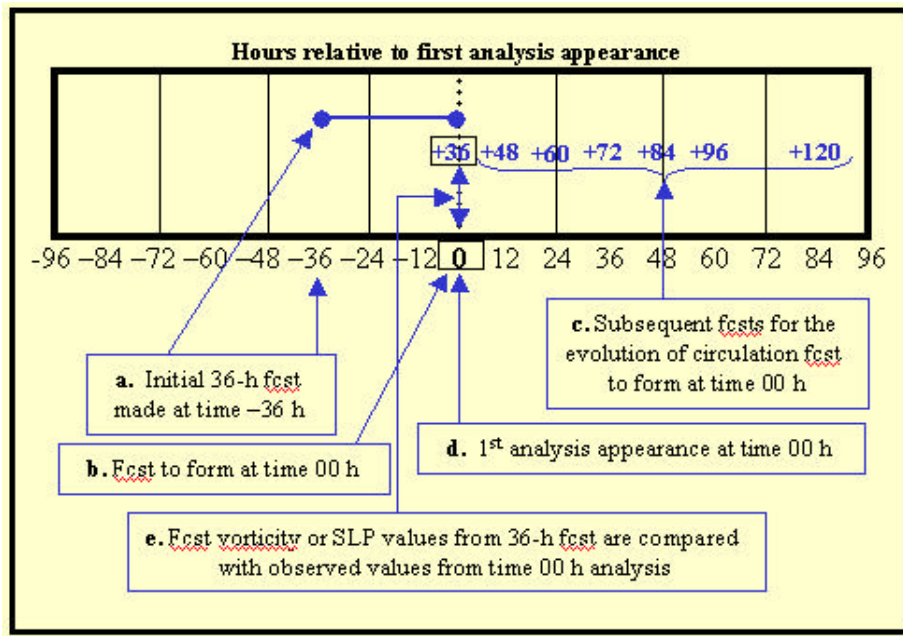


Figure 3.5. A 36-h NOGAPS forecast made at time -36 h (box a) indicates a predicted formation time of 00 h (box b).

Subsequent forecasts (box c) predict evolution of circulation. First analysis appearance at time 00 h (box d) results in no forecast timing error, and forecast values of vorticity or SLP are verified against observed values in time 00 h analysis (box e).

In Figure 3.6, assume that at time -36 h the NOGAPS makes a 24-h formation prediction (box a). This prediction would result in a formation at time -12 h (box b). Subsequent 36-, 48-, 60-, 72-, 84-, 96-, and 120-h forecasts predict the evolution of the circulation (box c). Because the circulation did not actually appear until the analysis at time 00 h, there was a 12-h early timing error in the 24-h formation prediction (box d). Verifying forecast variables such as vorticity or SLP can be accomplished in several ways. In this approach, the forecast values are verified against the observed values in the time 00 h analysis (box e).

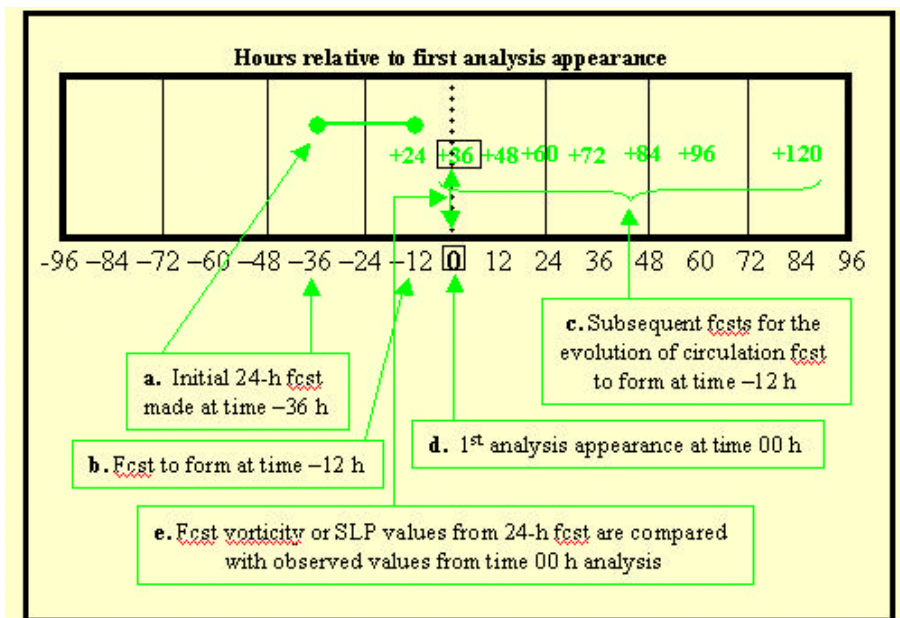


Figure 3.6. A NOGAPS 24-h forecast from time -36 h (box a) predicts circulation formation at time -12 h (box b).

Subsequent forecasts predict the evolution of the circulation that formed at time -12 h (box c). Actual circulation appearance occurs at time 00 h (box d), which results in a 12 h early timing error for the 24-h formation forecast. Forecast variables at 36 h are verified against observed values from the time 00 h analysis (box e).

Figure 3.7 is an example of the final timing error to mention. In this example, a 48-h forecast of formation is made at time -36 h (box a), so that the circulation formation is forecast at time +12 h (box b). Subsequent forecasts predict the evolution of the circulation that is forecast to appear at time +12 h (box c). Since the first actual appearance of the circulation is at time 00 h (box d), this results in a late timing error of 12 h for the 48-h formation forecast. In the case involving a late timing error, verification of forecast variables cannot be accomplished by comparison with the observed variables in the time 00 h analysis because the NOGAPS forecast was not predicting a formation to occur at this time. Instead, the observed variable values at analysis time +12 h are used to verify the 48-h forecast values (box e).



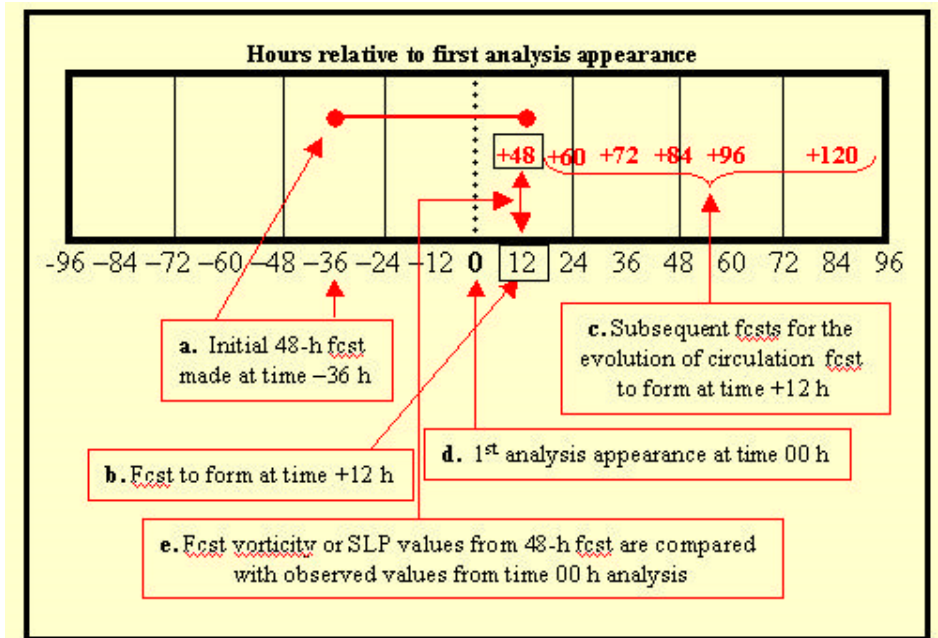


Figure 3.7. A NOGAPS 48-h formation forecast is made beginning from time -36 h (box a), which predicts circulation formation at time +12 h (box b). Subsequent forecasts are predictions for the evolution of the circulation predicted to appear at time +12 h (box c). The actual first analysis appearance occurs at time 00 h (box d), which results in a late timing error of 12 h for the 48-h forecast. Verification of forecast variables in the 48-h forecast is accomplished by comparison with observed values at time +12 h (e).

For simplicity, the example above included only three 36-h forecasts of formation that were either on-time (Figure 3.5), early (Figure 3.6), or late (Figure 3.7). Several more forecasts for the formation of a circulation could also occur beginning with a 120-h forecast and including every 12-h time step until formation. These forecasts for each circulation formation may include any combination of late and early timing errors as well as forecasts with no timing error. For each circulation formation, the subsequent part of the forecasts following formation predict the evolution of the circulation.

All formation forecasts are classified as early, on-time, or late. All groups of forecasts for all circulation formations yield several "strings" of forecasts. As demonstrated in Figures 3.5-3.7, the first potential verifying time for the forecasts in each string is at the time of actual circulation formation, and the subsequent 12-h forecast values after formation time are predictions for the evolution of the forecast circulation. Figure 3.8 is an example of three columns of verifications associated with a series of early formation forecast strings all initiated 72 h prior to actual formation. One "dimension" in this verification is in "columns" of forecasts having the same forecast interval (where the forecast interval ( $\tau$ ) can be +12 h, +24 h, +36 h,..., +120 h). Whereas each column in Figure 3.8 consists of forecasts having the same forecast  $\tau$ , these columns for verification do not depend on how late or early the timing error for the formation forecast was. The left-most dashed column in Figure 3.8 is comprised of 72-h evolution forecasts stemming from different early formation forecasts. The 72-h forecast at the top of this column is part of the forecast sequence subsequent to a 12-h formation forecast. The next forecast in this column is part of the sequence of forecasts stemming from a 24-h formation forecast, and so on. Since all 72-h forecasts in the left-most dashed column coincide with the analysis time 00 h, the 72-h forecast variable values would be verified against observed values in the 00 h analysis. The middle dashed column is comprised of all 84-h forecasts made in the group. These forecasts coincide with the circulation appearance at analysis time +12 h, so these forecasts would be verified against observed values

from analysis time +12 h. The right dashed column contains 96-h forecasts and these values will be verified against observed values from the +24 h analysis time. Thus, the second "dimension" in this verification is the times after actual formation.

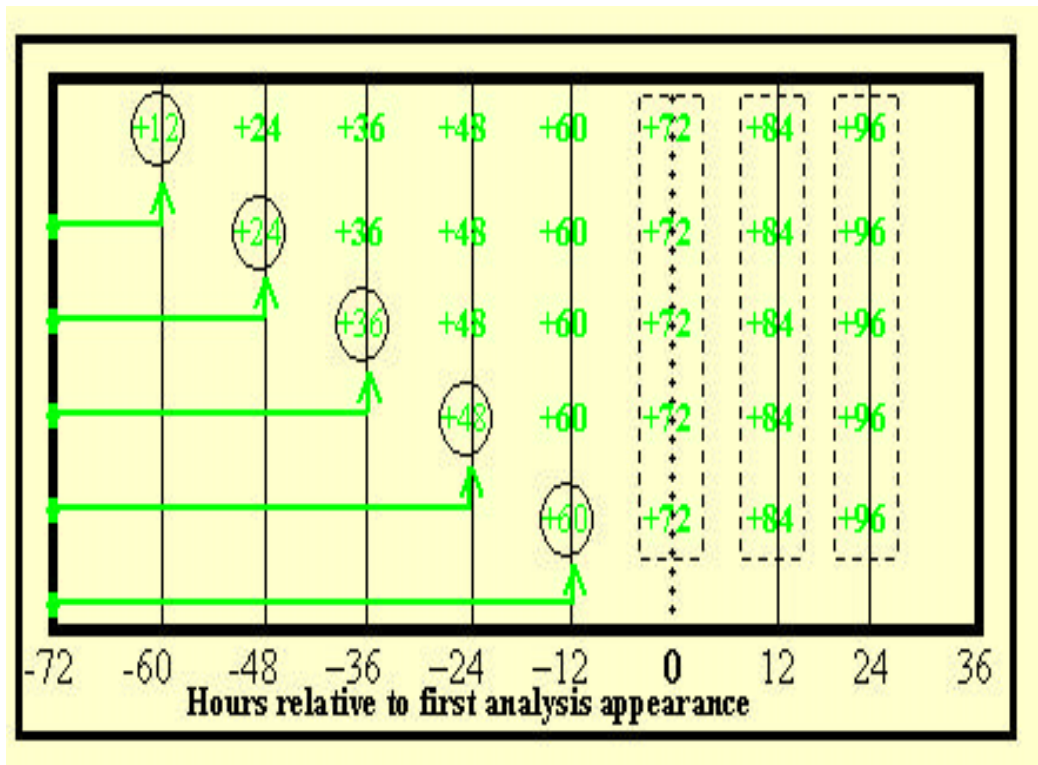


Figure 3.8. Series of early formation forecasts and their subsequent strings of evolution forecasts. All forecasts in the same column (having the same tau) will be verified against the same analysis time. That is, 72-, 84-, and 96-h forecasts will be verified against values from analysis times 00 h, 12 h, and 24 h, respectively.

Forecasts are first classified into the various categories in Table 3.1. Formation forecasts (and their subsequent evolution forecasts) from these categories are further subdivided into forecasts that are early, on-time,

or late. Formation forecasts having the same formation timing error are then categorized into groups of forecasts having the same forecast interval ( $\tau$ ) coincident on the same verifying analysis time (as demonstrated in Figure 3.8). Forecast variable values for these forecasts will be verified against that same analysis time. Figure 3.9 is a summary of the steps taken in grouping common forecasts for verification. For example, from all forecasts (box a) consider the formation forecasts for all circulations that formed in the eastern Atlantic, and persisted at least two days (box b), and were formation forecasts (and subsequent evolution forecasts) with early timing errors (box c). Consider only the 72-h forecasts that are to be verified with the 00 h analysis variables (box d). All forecasts meeting these criteria would be grouped together for verification.

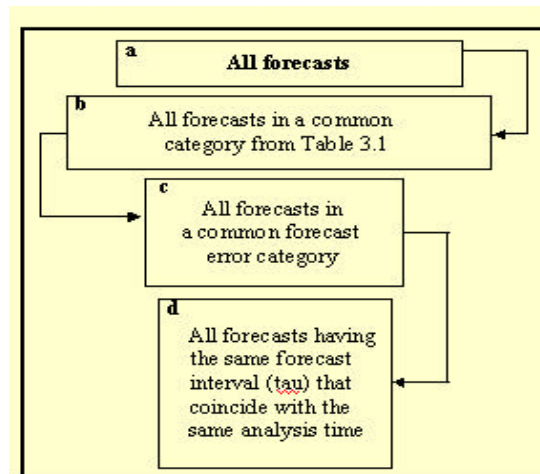


Figure 3.9. Description of the process for grouping forecasts for verification.

Once all forecasts with the same forecast interval ( $\tau$ ) that are to be verified at the same analysis time have been grouped, the variable values from individual

forecasts are compared to observed values at the verification analysis time to determine the error in each forecast. An average error is then calculated for the group. Graphs in the two "verification dimensions" are used to summarize the errors for the different forecast groups (Figure 3.10 - 3.15). Each graph is specific to a forecast variable, forecast timing error category, and category from Table 3.1. Each graph consists of several lines, and each line is comprised of several points. The points on each line are the average errors corresponding to forecast groups having the same forecast interval  $\tau$ , which is the first verification dimension. The series of points forming a line are different forecast groups having the same  $\tau$  that were verified against the same verifying analysis time, which is the second verification dimension. The groups of lines on each graph represent error lines for different analysis verification times.

The forecast errors for 850 mb relative vorticity with no formation forecast timing errors are shown in Figure 3.10. Consider the first dot, which is for all 12-h forecasts that verified on-time at the actual formation time. By the definition of formation, this is the first time that the 850-mb relative vorticity has just surpassed  $1 \times 10^{-5} \text{ s}^{-1}$  in both the forecast and the analysis. Thus, both values are just above the  $1 \times 10^{-5} \text{ s}^{-1}$  threshold and the difference (forecast error) must be small. For this same reason, small differences are expected for all other on-time forecasts. Successive dots in Figure 3.10 are for 24-h, 36-h, 48-h, and 60-h forecast intervals, all of which represent on-time forecasts verifying at longer forecast time intervals. No values are shown for longer forecast

intervals since the sample size is too small for significant values. These errors in forecast relative vorticity for on-time forecasts are not significant, with the majority of errors within  $\pm 0.4 \times 10^{-5} \text{ s}^{-1}$  for all forecast time intervals and at all verification analysis times.

The squares in Figure 3.10 are for verifications 12 h after formation time. Since all forecasts for this graph are for on-time formations, the differences between the lines connecting the on-time 00 h verifications and the +12 h verifications are for the error growth over that 12-h interval. Notice that the first forecast that can be verified 12 h after formation time is a 24-h forecast, which is the first square in Figure 3.10. The second square is for all 36-h forecast errors verifying at 12 h after formation time, etc. The sample sizes are such that forecast errors for intervals up to 72 h can be verified. Since all of these +12 h after formation error verifications in Figure 3.10 are small, the additional 12-h error growth is small for these on-time formation verifications.

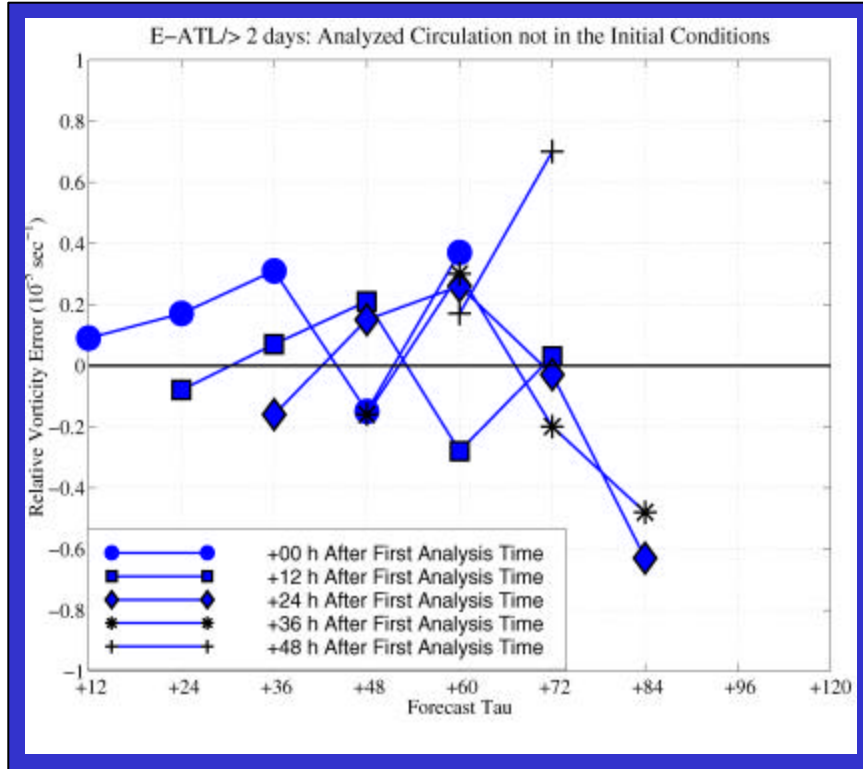


Figure 3.10. Average forecast values of relative vorticity for formation forecasts with no timing error made for circulations forming in the eastern Atlantic Ocean that lasted at least 2 days. As shown in the inset, the circles indicate all forecasts verifying at the formation time, so that the first dot is for all 12-h forecasts verifying on-time, the second dot for all 24-h forecasts verifying on-time, etc. The squares are the on-time verifications at 12 h after formation time, so the first square is for all 24-h forecasts, the second square is for all 36-h forecasts, etc. The remaining lines are for later on-time verifications at 24 h, 36 h, and 48 h after formation time, and each group begins with a longer forecast interval tau.

As shown in the inset of Figure 3.10, other verification times up to 48 h after formation time can be calculated for these on-time formation forecasts. For each

longer verification time, a 12-h longer forecast interval can be verified, but the sample sizes also limit the length of forecasts. Thus, the first entry on each line is 12 h later on the x-axis, and each successive line in Figure 3.10 is shorter. Notice that most of the values are small, so these on-time formation forecast error growths are small, except beyond 60 h. One interpretation is that NOGAPS has successfully formed a circulation, but then systematically under-amplifies this circulation relative to the real circulations that grow following formation.

Figure 3.11 is a similar summary of the average relative vorticity forecast errors for all forecasts with early formation timing errors made for circulations forming in the eastern Atlantic Ocean that lasted at least 2 days. Because these circulations were forecast to form at various times earlier than the observed formation time, it might be expected that the forecast circulations would have consistently higher relative vorticity values than observed. This error contribution may be regarded as a timing error resulting from an early formation forecast. In addition to the timing error resulting from the early formation timing error, there is also an inherent model error related to the increase in forecast interval.

Consider first the verifications at 00 h formation time (circles) in Figure 3.11. The first forecast interval that could have an early formation time (-12 h) and could be verified at 00 h is a 24-h forecast tau (first circle in Figure 3.11). Because this 24-h forecast had an additional 12 h growth period beyond the 12 h early forecast formation time before being verified at 00 h, the relative vorticity



error is positive ( $0.5 \times 10^{-5} \text{ s}^{-1}$ ). Similarly, the early 36-h and 48-h forecasts verifying at the 00 h formation time also had positive errors that can be attributed to an early timing error contribution. However, all of the longer forecast intervals (except 72 h) verifying at 00 h have negative relative vorticity errors rather than the expected positive timing error contributions. These negative errors are interpreted to arise from model errors that systematically under-forecast the real amplification of circulations and counter the expected positive timing error contribution.

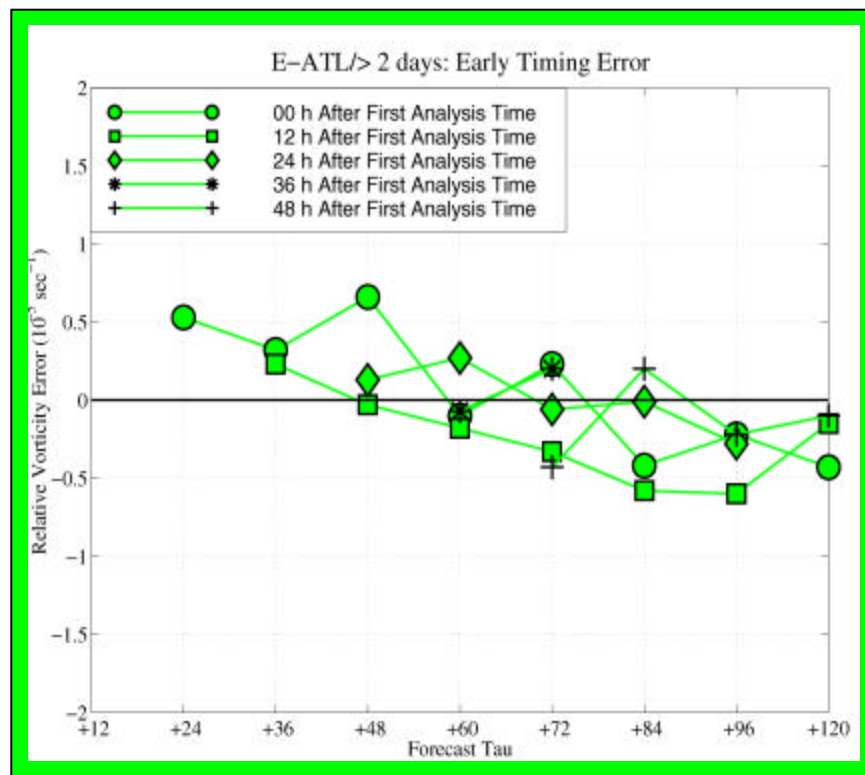


Figure 3.11. Average forecast errors for relative vorticity as in Figure 3.10, except for formation forecasts with an early forecast timing error made for circulations forming in the eastern Atlantic Ocean that lasted at least 2 days. Since an early 12-h timing forecast error requires at least a 24-h forecast, the first circle is a forecast interval tau of 24 h.

Figure 3.12 is a similar summary of the average relative vorticity forecast errors for all eastern Atlantic forecasts with late formation timing errors. Because these circulations were forecast to form at various later times than the observed formation time, it might be expected that the forecast circulations would lag in development compared to the actual circulations. This late forecast timing error would be manifest in forecast values of relative vorticity being consistently lower than the observed values.

The first forecast interval  $\tau$  that can be verified for a late formation is a 24-h forecast from 12 h prior to formation that verifies 12 h after formation, which is the first square in Figure 3.12. As expected, this value is negative ( $-1.0 \times 10^{-5} \text{ s}^{-1}$ ) for this late timing forecast error. Other longer term forecasts verifying 12 h after formation also have negative (or near-zero values), but not with increasingly large negative errors for larger forecast intervals. This error tendency is generally the same for the late formation forecasts verifying at later times after formation time (Figure 3.12). The interpretation is again that model forecast error has a larger contribution with increasing forecast interval than does the timing error contribution.

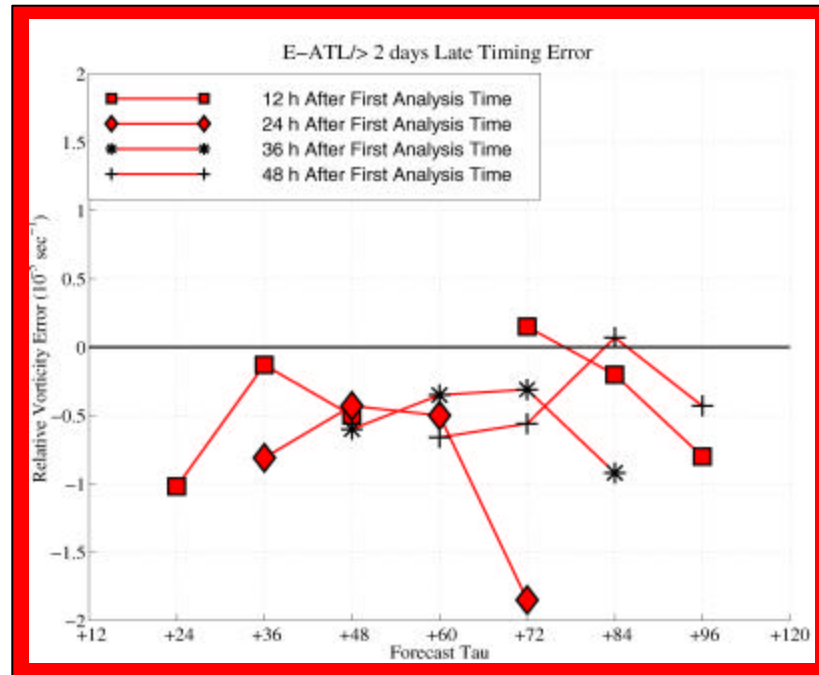


Figure 3.12. Average forecast errors for relative vorticity as in Figure 3.10, except for formation forecasts with a late forecast timing error made for circulations forming in the eastern Atlantic Ocean that lasted at least 2 days. The first forecast interval tau that can be verified for a late formation is a 24-h forecast from 12 h prior to formation that verifies 12 h after formation, which is the first square in the figure.

Figures 3.13-3.15 are similar to Figures 3.10-3.12, except that Figures 3.13-3.15 summarize the average SLP forecast errors for on-time, early, and late formation forecasts, respectively. These figures substantiate some of the tendencies observed in Figures 3.10-3.12.

Figure 3.13 is a summary of the average SLP forecast errors for formation forecasts with no timing error. Given that the forecast errors for 850-mb relative vorticity in Figure 3.10 were small for on-time forecasts, it was

expected that the SLP errors would also be small. Whereas the SLP errors are small for the on-time forecasts of 36 h through 72 h verifying at formation time (circles in Figure 3.13), the 12-h and 24-h forecasts are about 1 mb too deep. These overly deep SLP centers may arise from a heated land bias over Africa, but that would not be expected for formations over the eastern Atlantic. The other forecast errors in Figure 3.13 that are verified at later times after formation also have a tendency to be negative (forecast SLP too low), rather than being near-zero for on-time formation forecasts. Thus, SLP errors of the order of 1 mb may be representative of model uncertainty even when the 850-mb vorticity is correctly predicted.

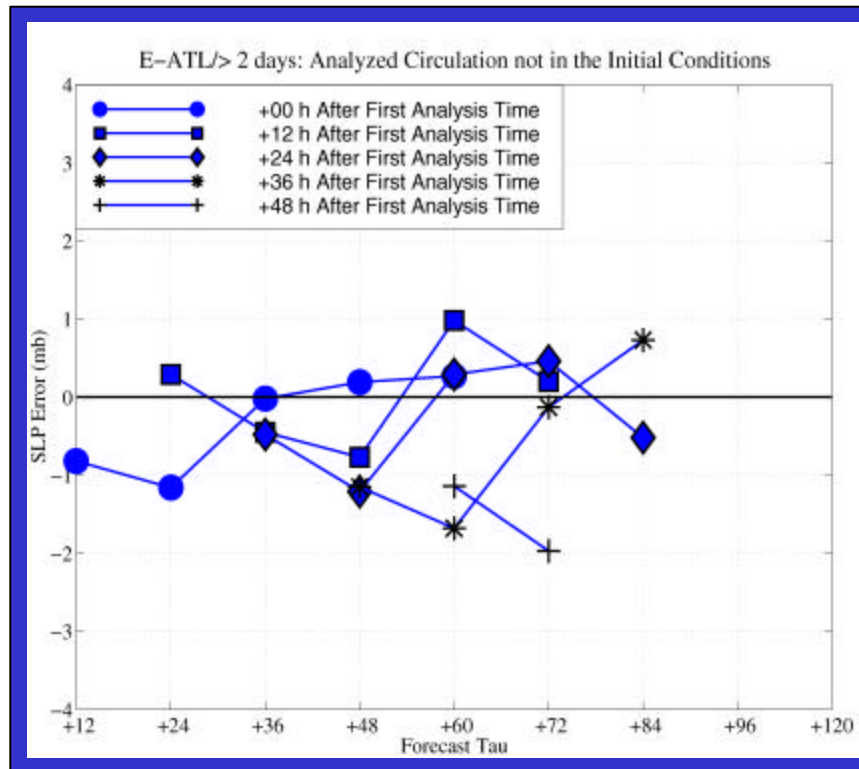


Figure 3.13. As in Figure 3.10, except for SLP errors for formation forecasts with no timing error made for circulations forming in the eastern Atlantic Ocean that lasted at least 2 days.

The average SLP forecast errors for formation forecasts with an early timing error are summarized in Figure 3.14. The average errors are negative (forecast SLP too low) for 24-h and 36-h forecasts verified at the first analysis time, which is expected for an early timing error contribution. That is, the early formation timing error causes the model 850-mb relative vorticity to be too large (Figure 3.11) for the 24 h and 36 h forecasts, so one would expect the corresponding SLP forecasts to be too low. Just as this trend is reversed at longer forecast intervals for relative vorticity forecasts verifying at the formation time (Figure 3.11), the SLP errors become positive at 96 h and 120 h. For nearly all other analysis times and forecast intervals, average SLP errors are positive, which indicates the forecast circulations are under-developed (not as deep) with respect to the actual circulations. This under-development suggests that the positive errors arise from model errors that systematically under-forecast the real amplification of circulations and counter the expected early timing error contribution.

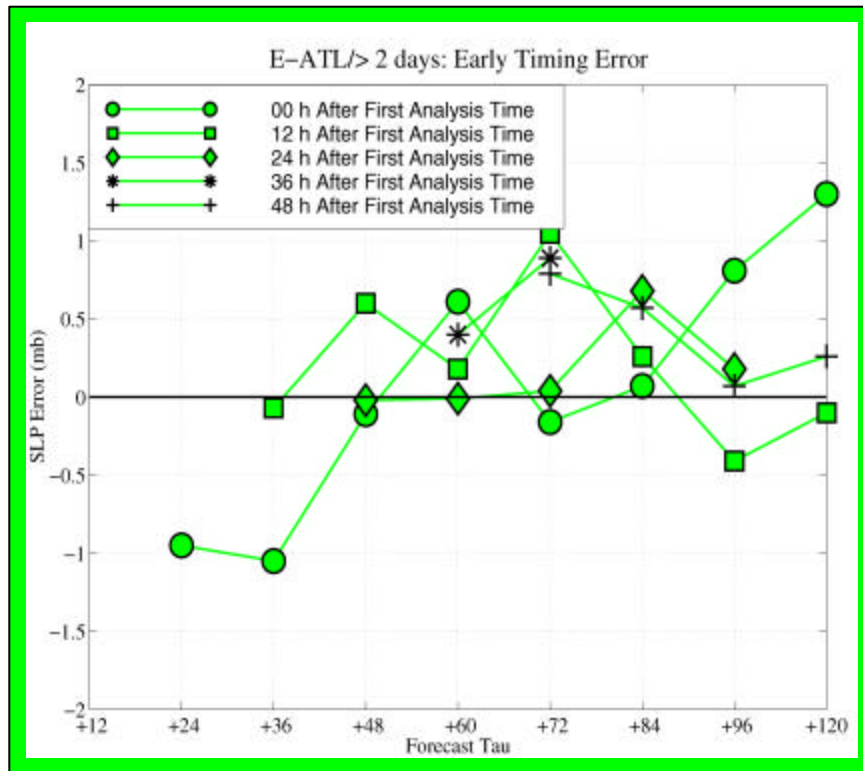


Figure 3.14. As in Figure 3.11, except for SLP forecast errors for formation forecasts with an early forecast timing error made for circulations forming in the eastern Atlantic Ocean that lasted at least 2 days.

Figure 3.15 is a summary of average SLP forecast errors for formation forecasts with a late forecast timing error. Positive SLP errors for 24-h forecasts verified 12 h after the first analysis appearance are as expected for formation forecasts with a late timing error. However, the expected result of increasingly greater positive SLP errors is not evident for the verifications 24 h and 36 h after formation time (diamonds and asterisks in Figure 3.15). Some evidence exists for a too high SLP for verifications at 48 h after formation, but the magnitude is less than 1.25 mb, which may not be significant in view of the

scatter in these SLPs. Interpretation of these errors is again that model forecast error has a larger contribution with increasing forecast interval than does the late timing error contribution.

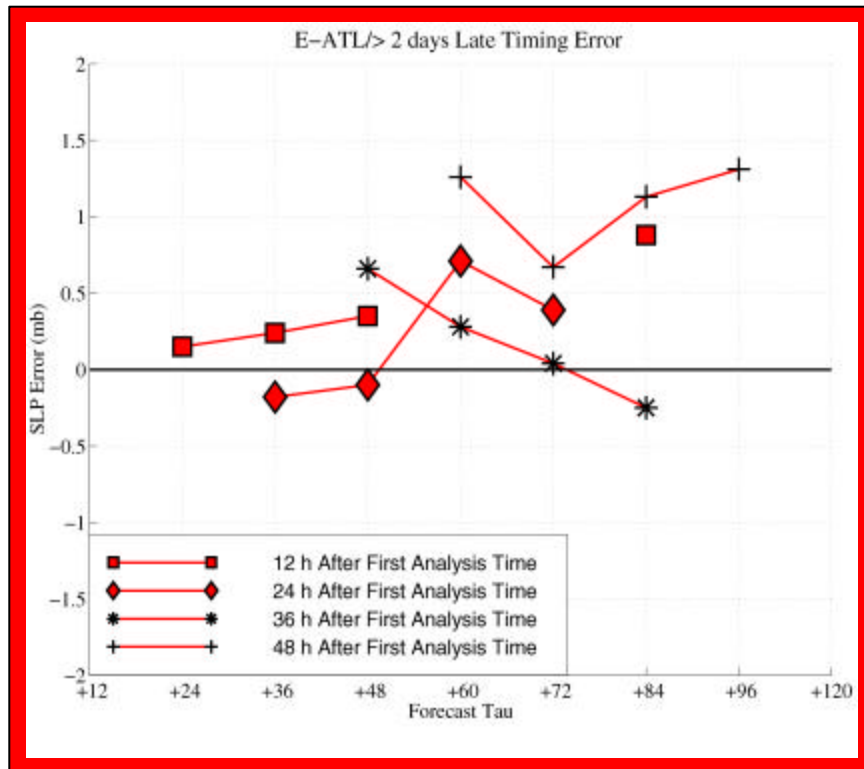


Figure 3.15. As in Figure 3.12, except for SLP forecast errors for formation forecasts with a late forecast timing error made for circulations forming in eastern Atlantic Ocean that lasted at least 2 days.

## 2. Verifications at Times of Vorticity Thresholds or as at Tropical Storm Warning

For this method of verification, forecast values related to the circulations are compared with the analyzed values at the first time that the circulation reaches a relative vorticity value of  $2.5 \times 10^{-5} \text{ s}^{-1}$  and  $3.0 \times 10^{-5} \text{ s}^{-1}$ .

A third verification is at the time the first tropical cyclone warning was issued by the National Hurricane Center (NHC) for the circulation, which occurs when the circulation reached at least tropical storm strength. The tracks of all eastern Atlantic circulations that reached a relative vorticity value of at least  $2.5 \times 10^{-5} \text{ s}^{-1}$  are depicted in Figure 3.16 with the threshold points that exist for each track marked appropriately.

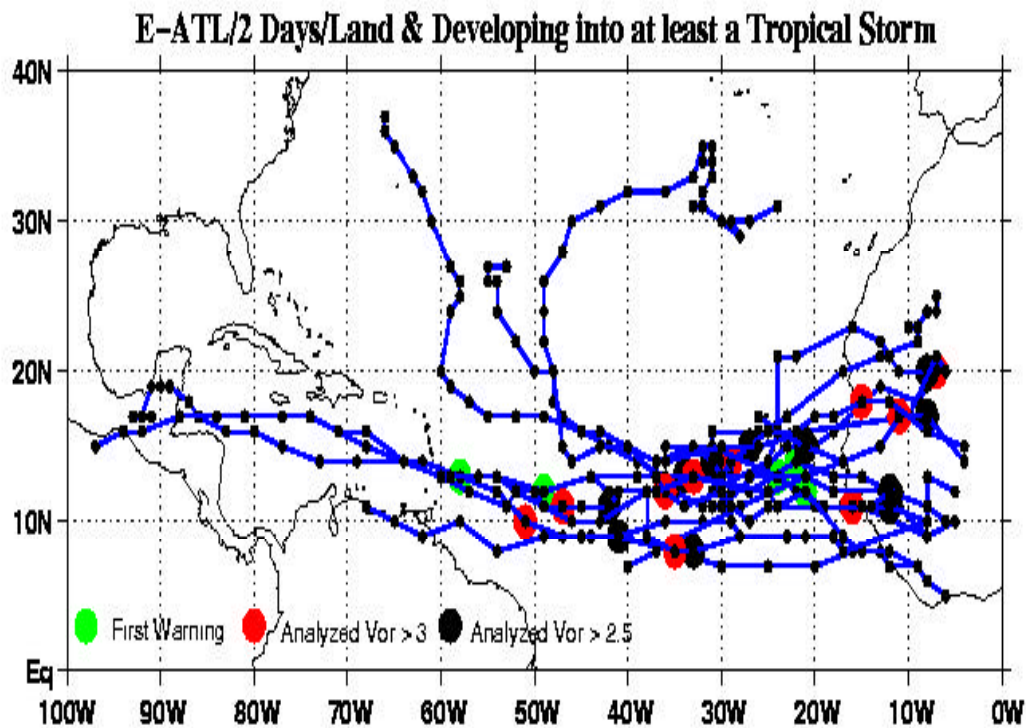


Figure 3.16. Tracks of all eastern Atlantic circulations that reached tropical storm strength. Colored symbols indicate points when each circulation reached a vorticity value of  $2.5 \times 10^{-5} \text{ s}^{-1}$  (black), reached a vorticity value of  $3.0 \times 10^{-5} \text{ s}^{-1}$  (red), and had a tropical storm warning issued (green).

Average vorticity, SLP, and size errors (Figures 3.17 – 3.19), indicate that the circulations are under-forecast



at the first verification time when the analyzed vorticity value reaches  $2.5 \times 10^{-5} \text{ s}^{-1}$ . For example, the under-forecasts of relative vorticity exist for all forecast intervals starting with  $0.5 \times 10^{-5} \text{ s}^{-1}$  at 12 h and increasing to  $1.0 \times 10^{-5} \text{ s}^{-1}$  for the 120-h forecasts. Given the weaker cyclonic circulations at 850 mb, it is not surprising that the forecast SLP's are generally too high through most of the forecast periods (Figure 3.18). The consistent under-forecast of size at all forecast intervals prior to when the circulation reached  $2.5 \times 10^{-5} \text{ s}^{-1}$  is even more striking (Figure 3.19).

By the time the circulations have reached the threshold vorticity value of  $3.0 \times 10^{-5} \text{ s}^{-1}$ , the magnitudes of the under-forecast errors have all increased. For all forecast times, the average forecast relative vorticity values are too low (Figure 3.17), the average forecast SLP values are too high (Figure 3.18), and the average forecast sizes are too small (Figure 3.19). The surprising result is that marked reductions in the average forecast errors of all three variables have occurred by the time a tropical storm warning has been issued for the circulation. Based on this limited sample, these forecast verifications indicate a NOGAPS tendency to under-develop Atlantic tropical circulations at early stages before they eventually develop into tropical storms. This tendency is somewhat corrected by the time a circulation has been issued a tropical storm warning by the NHC. Further analysis is needed to explain why the under-forecast tendency during the early stage would be offset as the circulation actually was amplifying.

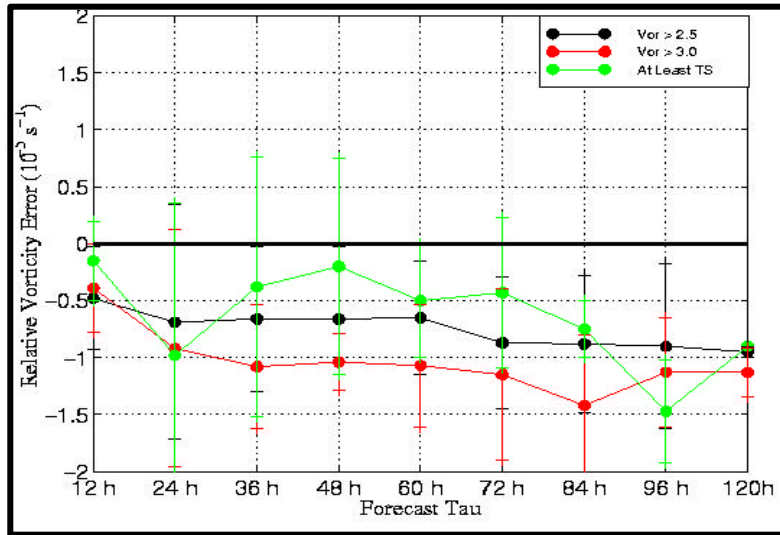


Figure 3.17. Summary of forecast relative vorticity error for circulations at time when the circulations reached a vorticity value of  $2.5 \times 10^{-5} \text{ s}^{-1}$  (black), reached a vorticity value of  $3.0 \times 10^{-5} \text{ s}^{-1}$  (red), and had a tropical storm warning issued (green).

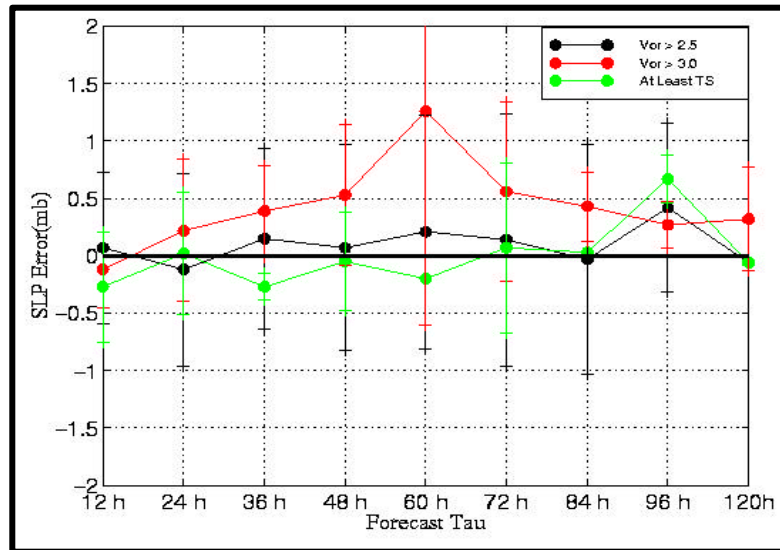


Figure 3.18. Summary of forecast SLP errors for circulations at time when the circulations reached a vorticity value of  $2.5 \times 10^{-5} \text{ s}^{-1}$  (black), reached a vorticity value of  $3.0 \times 10^{-5} \text{ s}^{-1}$  (red), and had a tropical storm warning issued (green).

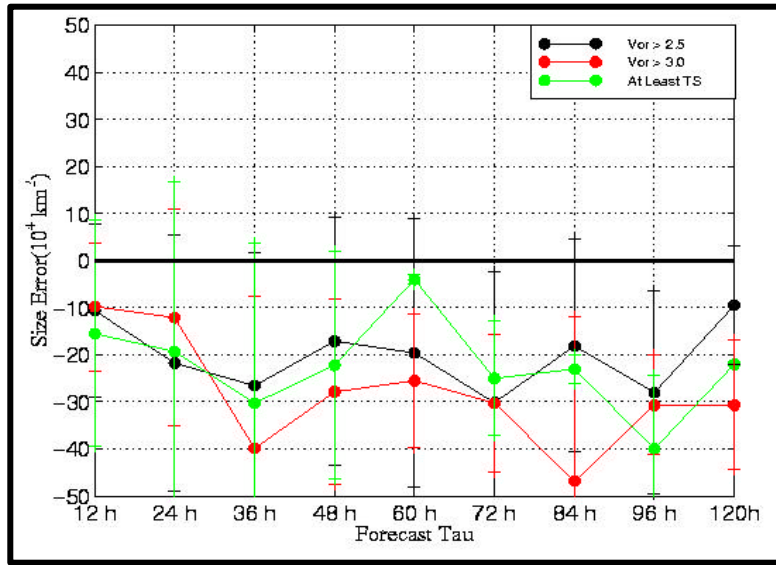


Figure 3.19. Summary of forecast size errors for circulations at time when the circulations reached a vorticity value of  $2.5 \times 10^{-5} \text{ s}^{-1}$  (black), reached a vorticity value of  $3.0 \times 10^{-5} \text{ s}^{-1}$  (red), and had a tropical storm warning issued (green).

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#### IV. SUMMARY AND CONCLUSIONS

The performance of NOGAPS in predicting the formation of circulations in the tropical North Atlantic is assessed by tracking 121 circulations from 25 July - 31 October 2001. A new tool called Tropical Cyclone Vorticity Tracking Program (TCVTP) developed by Professor Patrick Harr tracks circulations by identifying circulations in NOGAPS 850 mb relative vorticity analysis and forecast fields that have a value of at least  $1.0 \times 10^{-5} \text{ s}^{-1}$ . An ellipse is fit to the outer closed vorticity contour to define the size of the circulation. Identified circulations are linked together to form tracks when distance and movement criteria are met.

The circulations forming in a semi-permanent vorticity maximum over South America were eliminated from future analysis since they were not related to subsequent tropical formation over the Atlantic. The remaining circulations were categorized according to whether they formed over Africa, the eastern Atlantic Ocean, or the western Atlantic Ocean, the length of time appearing in analyses, and whether the forecast for their formation was early, late, or on-time.

Only 19 tracked circulations formed in the western Atlantic (west of  $40^\circ \text{ W}$ ) formation zone. This relatively small number of cases prevented detailed analysis because too few tracks were available to reveal any substantial systematic model trends. Before any conclusions can be drawn regarding the performance of NOGAPS in predicting

circulation formation in the western Atlantic, a study including more circulations is necessary. Since the majority of the circulations in this study formed in the eastern Atlantic formation zone, this region is the focal point of further analysis.

## **A. FORECAST TIMING ERRORS**

### **1. Formation Forecast Errors**

All circulation forecasts were analyzed to assess how well the model prediction for formation agreed with observed formation events. Forecasts were either on-time, early, or late. The strictest criteria were set for determining an on-time forecast. A more relaxed condition was also tested wherein a  $\pm 12$ -hour error was allowed, with corresponding modifications in the definitions of late and early formation errors.

#### ***a. Western Atlantic***

For the 19 circulation formations in the western Atlantic, 50 forecasts were made prior to the actual appearance of a vorticity circulation in an analysis. When applying the strict (relaxed) definition of on-time to these forecasts, 23 (39) were on-time, 18 (5) were early, and 9 (6) were late. For circulations tracked at least 2 days, the number of on-time, early, and late forecasts were 11, 5, and 4, respectively. The circulations lasting less than two days had more than twice as many early formation forecast errors than late errors (13 versus 6). A data set consisting of more western Atlantic circulations would be required before assessing any formation forecast error trends in NOGAPS.

### ***b. Eastern Atlantic***

This zone yielded several interesting error trends for the formation forecast assessment of NOGAPS. A total of 226 forecasts were made for the circulations forming in the eastern Atlantic. Without considering the forecast time relative to first analysis appearance, 91 (170) of these were on-time, while 135 (56) were either early or late following the strict (relaxed) criterion for an on-time forecast.

Focusing on the eastern Atlantic circulations that had tracks of at least two days, 35%, 11%, and 54 % of forecasts for circulations first appearing over the eastern Atlantic Ocean were on-time, early, and late, respectively. On the other hand, for circulations forming over Africa, 42%, 36%, and 21% of forecasts were on-time, early, and late, respectively. This trend continues when examining the eastern Atlantic circulations tracked less than 2 days. For circulations that formed over the ocean, or were tracked over the ocean at some point in their history, 19%, 19%, and 62% of the forecasts were on-time, early and late, respectively. For circulations that never tracked over the ocean 58%, 32%, and 10% of the forecasts were on-time, early, and, late, respectively. It is concluded based on this sample that circulations forming over Africa are forecast by NOGAPS to form too early while circulations forming over the eastern Atlantic are forecast to form later than they actually do.

With forecasts made greater than 3 days prior to formation, it is more likely (unlikely) to have early (late) forecasts as integrations only take place out to 120

h. This is borne out for both strict (only 1) and relaxed (0) late forecasts. The one late forecast and seven of the early forecasts were within 12 h, so with the relaxed criterion the on-time performance (71%) is quite good compared to the early forecasts.

With forecasts made less than 2 days prior to formation, the predominant tendency would be for more late forecasts than early forecasts. This is borne out for the strict and relaxed cases as well. In the latter case, an appearance in the initial fields of the -12 h forecast would satisfy the relaxed criterion. The 76% relaxed on-time performance in these short-term forecasts is considered favorable.

For the intermediate intervals, both early and late forecasts might be expected, but with the strict definition a slight tendency for early forecasts exists. With the relaxed definition, the early and late forecasts are essentially the sample, and 49 of 73 (67%) of the forecasts are on-time. In all three categories, relaxed on-time is close to 70% (as earlier summarized), indicating there is no dependence on times forecasts were made relative to actual formation.

## **2. Skipped Forecast Periods**

Another result from the circulation formation predictions was the assessment of skipped forecasts during the period. In these instances, a forecast for formation is made at some point prior to actual formation. A skipped forecast is defined if at some time between the initial forecast of formation and the actual formation event one or more model integrations do not include a formation



prediction for the circulation previously forecast to form. For the 85 formation forecasts made for eastern Atlantic circulations forming over Africa, there were only five of these skip occurrences. In contrast, 12 skips occurred within the sequences of 54 formation forecasts for circulations forming over the eastern Atlantic Ocean. This higher frequency of skips for formation forecasts over the ocean may indicate a model uncertainty arising from sparse data coverage over water. An alternate explanation may be that stronger fluctuations in the relative vorticity forecasts occur for circulations forming over water due to the importance of moisture processes in the early stages of circulations.

### **3. End-of-track Forecast Errors**

An assessment was also conducted of forecasts for the end of the circulation. Specifically, forecast circulations that appeared in the analyses for less than 48 hours were examined to determine if the end of their existence was accurately predicted. In the eastern Atlantic, 29 circulations formed that lasted less than 2 days. For these 29, 89 forecasts were made between the first and last times these circulations appeared in analyses. Of the 89 forecasts, over half (47) were predictions that the circulation would persist beyond its actual final analysis appearance. These errors can be regarded as over-forecasts in the sense that NOGAPS is predicting circulation life spans that are longer than observed. A similar trend was found for the circulations forming in the western Atlantic that lived less than 2 days, where 19 of 24 forecasts made between formation and final analysis appearance predicted that the circulation

would persist beyond the observed final analysis. The validity of this result is suspect due to the relatively small number of forecasts included in the western Atlantic group.

#### **4. False Alarms**

For this limited study in the tropical North Atlantic, 121 circulations were tracked. Since 14 false alarms met the criteria outlined in section III, about 12% of the forecast circulations were false alarms. Whereas a slight majority of these false alarms (8) took place in the western Atlantic formation zone, the percentage of false alarms is considerably higher than in the eastern Atlantic because of the smaller number of circulations that form in the western Atlantic. Even though this is not a large percentage of false alarms, additional study is necessary to help the forecaster distinguish between false alarms and actual circulations.

#### **B. VARIABLE VERIFICATION**

Verification of the various forecast variables was performed in two ways. The first method described in section III involved verifying the case-average variable values from forecasts against the average values at some time in the analysis sequence. The other method described in section III verified the case-average forecast values of circulations against values observed when those circulations had reached relative vorticity values of  $2.5 \times 10^{-5} \text{ s}^{-1}$  and  $3.0 \times 10^{-5} \text{ s}^{-1}$ , as well as at the time when warnings were first issued by the National Hurricane Center for the circulations.

## **1. Verifications Summarized at Analysis Times**

This method was only applied to all eastern Atlantic circulations that appeared in analyses for at least 48 hours because the number of circulations in the western Atlantic was too small for meaningful statistics. For the eastern Atlantic circulations, predicted values of relative vorticity and SLP were validated for all circulations forecasts having late timing errors, early timing errors, and no timing error. Forecasts were also categorized by whether the circulation formed over Africa or over the eastern Atlantic Ocean, but this grouping did not reveal any tendencies based on formation region.

An initial tendency for the verification of forecast values of relative vorticity in forecasts having early timing errors is for over-forecast values of relative vorticity. This overly vigorous circulation is expected because the circulation had formed early in the model and continued to strengthen until verification time of formation. Compared with the strength of the circulation that has just formed, the forecast relative vorticity should be greater. However, at times greater than 48 h in the forecast, the model tends to under-forecast the relative vorticity. One interpretation is that the forecast circulations have already reached a maximum development and are beginning to dissipate, while the actual circulations continue to develop, or amplify more rapidly in nature. This result may be a combination of dispersive or physical errors, increased forecast length, and an increased timing error. If the dispersion is too large or physical processes are poorly represented, the

magnitude of the error may increase with time, while the early timing error would normally cause the forecast circulations to be over-developed.

Verification of the average SLP for eastern Atlantic circulations with an early forecast timing error indicates that short-term model forecasts are accurate ( $\pm 0.9$  mb) in predicting the SLP of the forming circulations. However, the model tendency beyond 48 hours is to under-forecast the predicted value of SLP, and thereby the forecast circulation is not as deep as it is in nature. Complicated and diverse surface processes are involved in the prediction of SLP. Regardless, this SLP under-forecast is consistent with the under-forecast relative vorticity beyond 48 h.

An initial tendency for the verification of forecast values of relative vorticity in forecasts having late timing errors is for under-forecast values of relative vorticity (negative average errors). This error is expected because the circulation had not yet formed in the model when the actual circulation was strengthening. Compared with the strength of the circulation that had already formed, the forecast relative vorticity should be less. Longer-term forecasts also have negative (or near zero values), but not with increasingly large negative errors for larger forecast intervals. The interpretation is that model forecast error has a larger contribution with increasing forecast interval than does the timing error contribution.

Verification of the average SLP error in eastern Atlantic circulations with late forecast timing errors

indicates positive errors for 24-h forecasts verified 12 h after the first analysis appearance. However, the expected result of increasingly greater positive errors does not occur. As with the verification of relative vorticity for forecasts having late timing errors, interpretation of the errors is again that model forecast error has a larger contribution with increasing forecast interval than does the timing error.

## **2. Verifications at Times of a Vorticity Threshold or an Issued Warning**

Average forecast values of relative vorticity, SLP, and the size parameter indicate a tendency for the model to under-forecast circulation development by the time the analyzed relative vorticity has reached a value of at least of  $2.5 \times 10^{-5} \text{ s}^{-1}$ . These errors are even greater at the time the analyzed relative vorticity values have reached  $3.0 \times 10^{-5} \text{ s}^{-1}$ . However, this tendency is reversed as the model adjusts to the environmental changes occurring around the developing cyclone. By the time a tropical storm warning was issued by the NHC, the average error is reduced in the forecasts of relative vorticity, SLP, and size. Further analysis is needed to explain why the under-forecast tendency during the early stage would be offset as the circulation actually was amplifying.

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## V. RECOMMENDATIONS FOR FURTHER STUDY

The use of the TCVTP in assessing model performance in the prediction of tropical circulation formation should be continued in other studies. Specifically, subsequent studies in the following list would be beneficial to tropical cyclone formation prediction assessment while also documenting the real-time potential of the TCVTP:

- Further analysis based on a multiple year sample of circulations in the tropical Atlantic.
- Further analysis including a larger sample of circulation formations in the western Atlantic zone.
- Further study of forecast verification using tropical storm/tropical depression threshold.
- Further study that attributes model performance to specific formation variables.
- Comparative studies of circulations forming in different tropical cyclone basins.
- Study that applies the TCVTP to other global numerical models for comparison with NOGAPS.

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